

NEUTRINO OSCILLATIONS

**Recent developments,
future prospects**

OVERVIEW

- **Neutrinos and oscillations**
- **Oscillation evidence I:**
atmospheric neutrinos
- **Oscillation evidence II:**
solar neutrinos
- **Oscillation evidence III:**
accelerator neutrinos
- **MiniBooNE I: beamline and detector**
- **MiniBooNE II: signal, backgrounds,
events!**

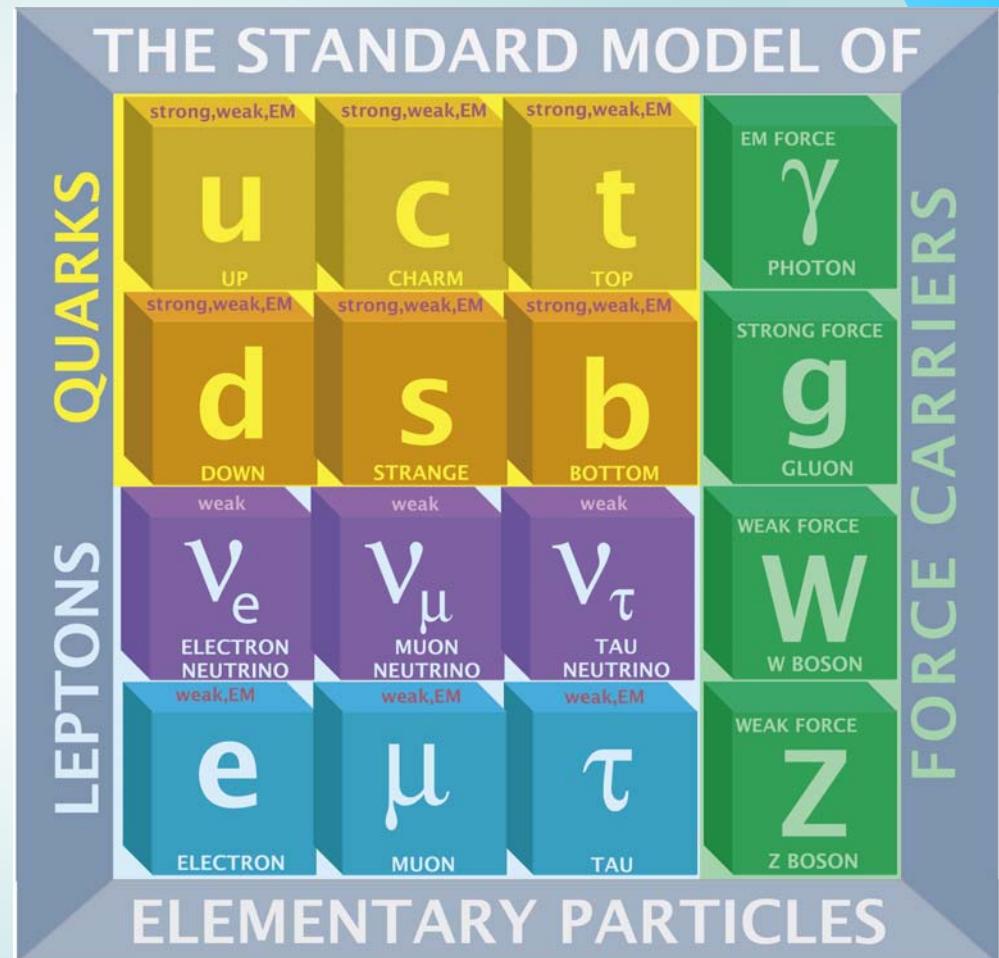
What's a neutrino?

Four forces:

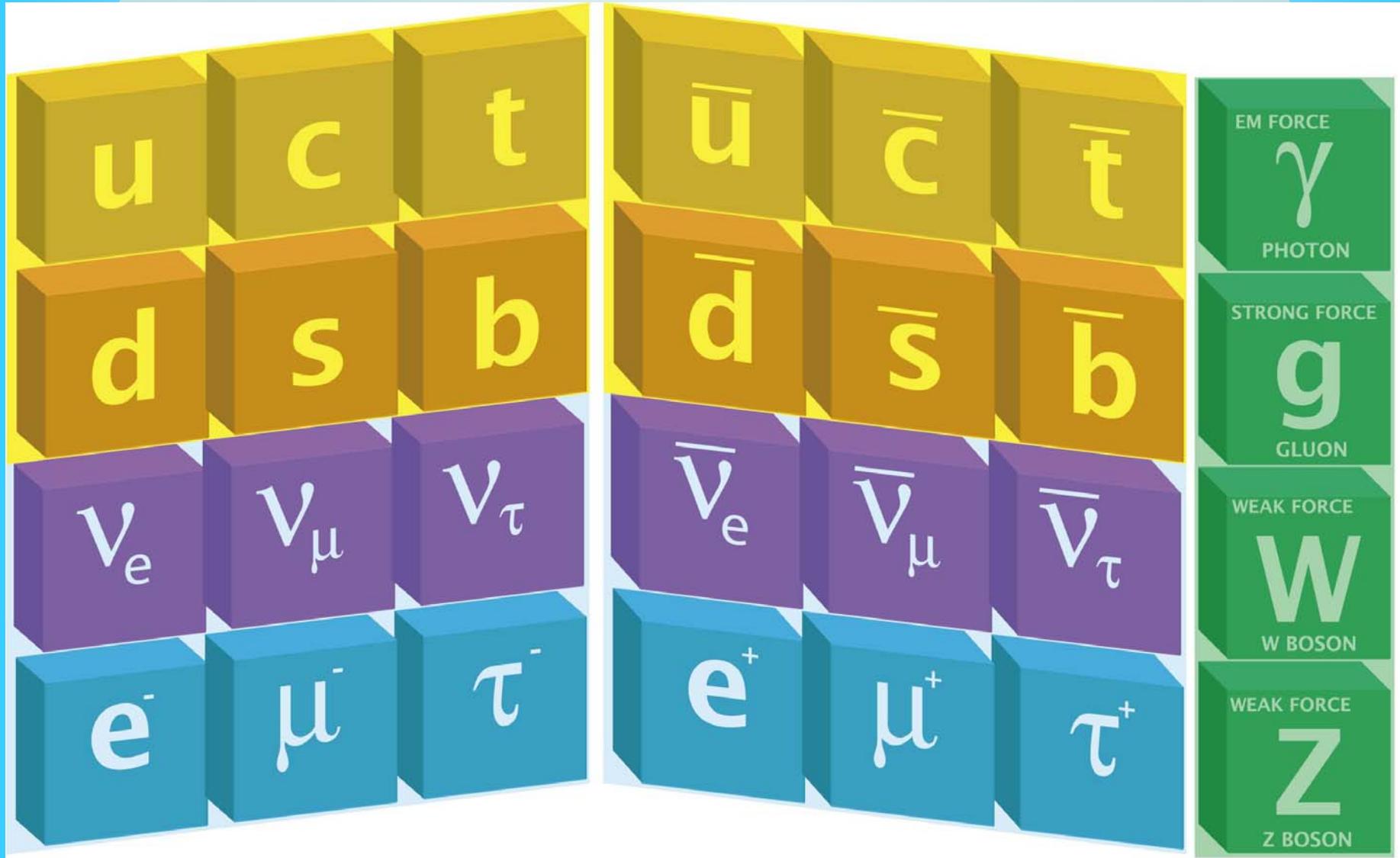
- Gravity
- Electromagnetism
- Strong
- Weak

Three particle types:

- quarks (S, W, EM)
- leptons (W, EM)
- force carriers



What's a neutrino?



NEUTRINO OSCILLATIONS

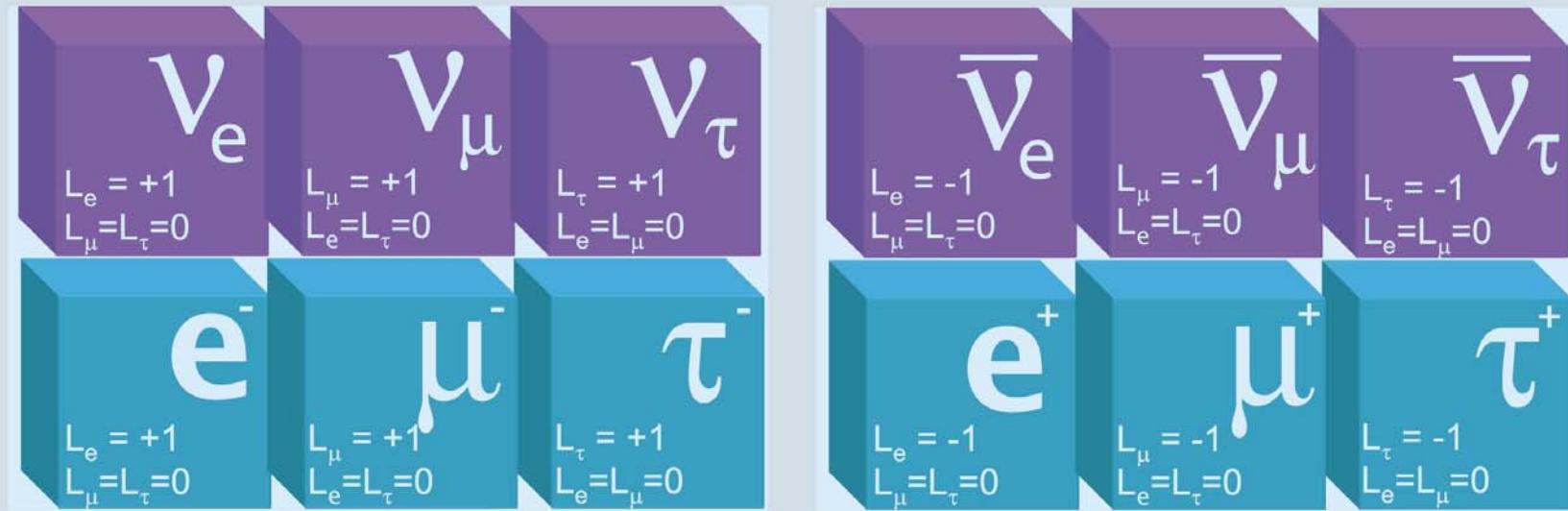
according to the Standard Model...

charged lepton masses (measured):	neutrinos (theory: ZERO); current limits:
e: 0.511 MeV	$\nu_e < 3\text{eV}$
μ : 105.6 MeV	$\nu_\mu < 190 \text{ keV}$
τ : 1777 MeV	$\nu_\tau < 18.2 \text{ MeV}$

interactions obey
conservation rules:

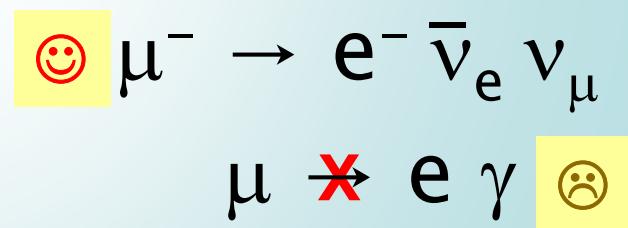
- electric charge
- momentum
- energy

according to the Standard Model...

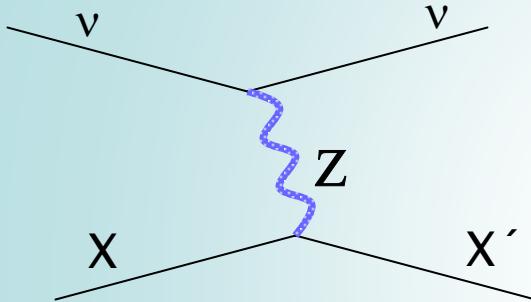
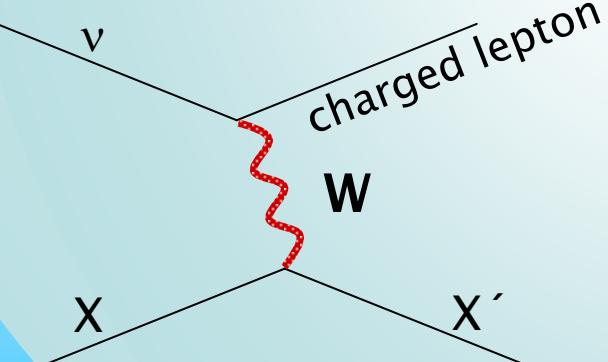


interactions obey
conservation rules:

- electric charge
- momentum
- energy
- lepton flavor



tell-tale leptons...

- Neutrinos interact weakly via:
 - **neutral current:** **neutral** final state lepton
$$\nu X \rightarrow \nu X'$$
neutrino UNSEEN!
∴ no flavor identifier
 - **charged current:** **charged** final state lepton
lepton tags flavor
$$\nu_\mu X \rightarrow \mu^- X'$$
$$\nu_e X \rightarrow e^- X'$$
; etc.)

generic neutrino experiment: make 'em...

- neutrinos come from two places:
 - nuclear processes (fission and fusion)
 - low energies (MeV and less)
 - only electron-type (ν_e or $\bar{\nu}_e$)
 - isotropic (all directions)
 - particle decays (e.g: $\pi^+ \rightarrow \mu^+ \nu_\mu$; $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$)
 - higher neutrino energies possible
 - can direct neutrinos by directing parent particles

Making
neutrinos...

... requires making
particles which decay
into neutrinos ...

...which you accomplish
by slamming protons
into a target, ...

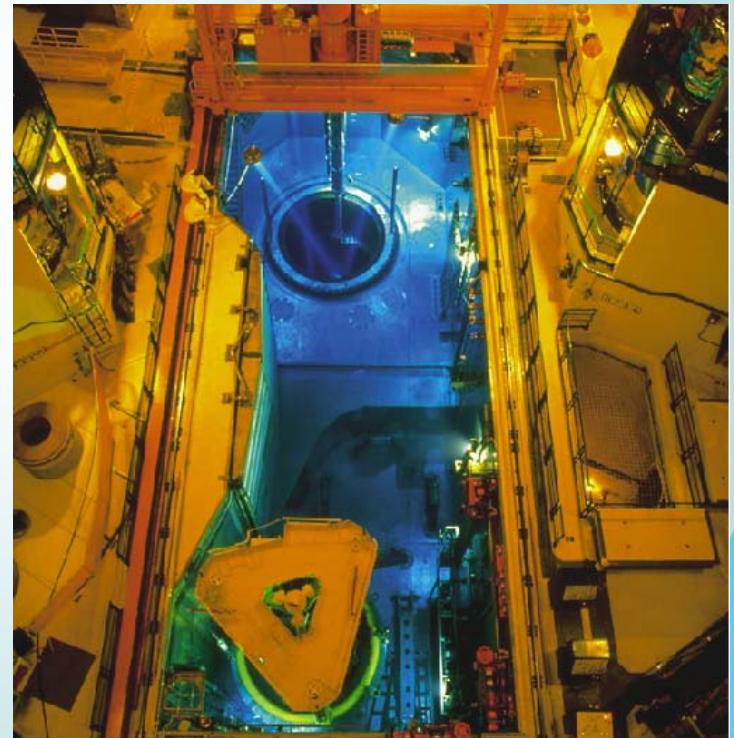


(... and perhaps filtering
out the leftovers).

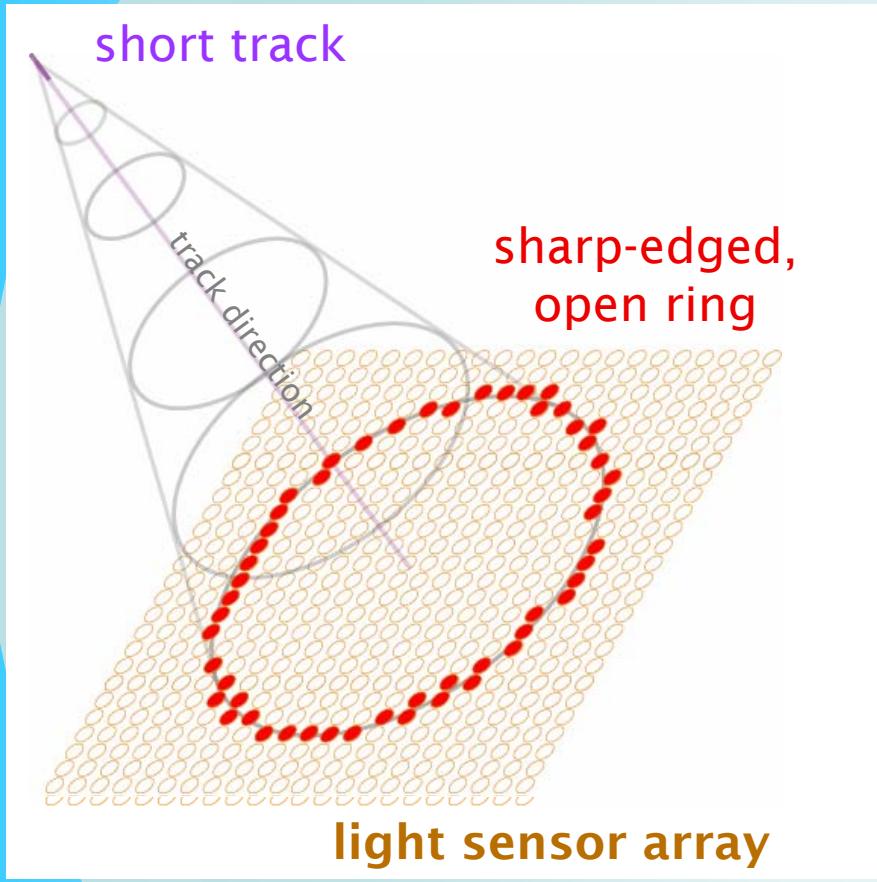
...letting the secondaries
decay ...

generic neutrino experiment: take ‘em...

- neutrinos interact WEAKLY (i.e., with low probability), so large numbers of neutrinos (high flux) and large detectors (high mass) are needed to obtain reasonable event rates
- must balance large detector masses with adequate detector sensitivity (“active volume”) and cost
- Čerenkov radiation: if particle’s speed $> c_{\text{medium}}$, get Čerenkov light

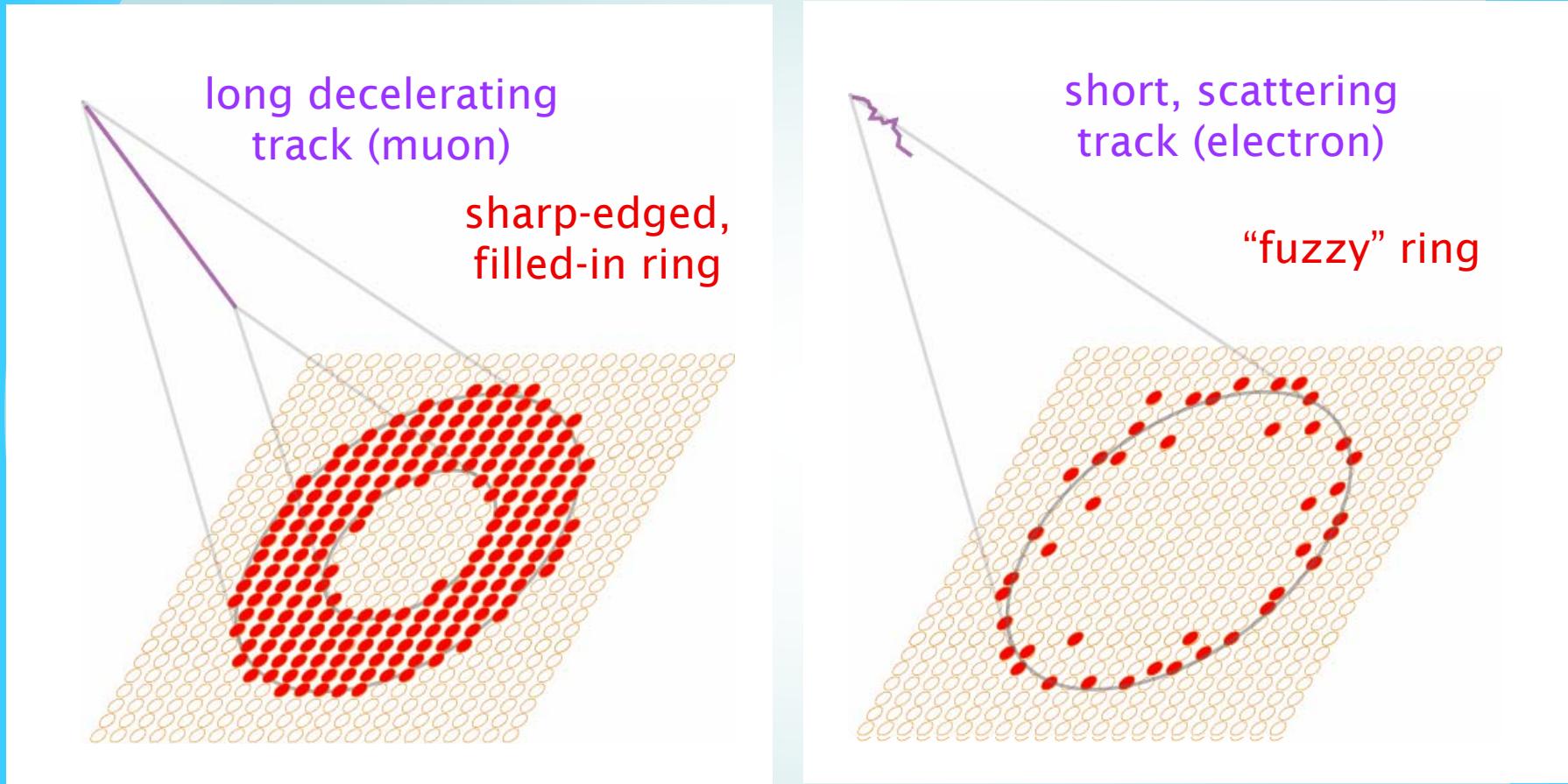


reading the rings...



- Čerenkov photons are emitted at a specific angle, and map out a cone as they move away from the track
- different kinds of particles make different tracks and therefore produce different kinds of rings

reading the rings...



what you see? what you get?

- only “see” charged particles
- particle identification is a challenge
- mass threshold constraints: can you pay the energy price to create a muon or tau?
- conservation constraints: no low energy charged current scattering from protons:
 - CC: $\nu_e n \rightarrow e^- p$ YES $\nu_e p \rightarrow e^- X^{++}$???
 - NC: $\nu_e p \rightarrow \nu_e p$ YES $\nu_e n \rightarrow \nu_e n$ YES (hard)

what's oscillating?

Quantum mechanical phenomenon

Two generation case:

WEAK states ν_μ, ν_e vs. **MASS** states ν_1, ν_2

Linear combinations:

$$|\nu_e\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle$$

create: **WEAK** (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$) state at $t = 0$

propagate: ENERGY (**MASS**) states for later t

if $m_1 \neq m_2$, propagation wavelengths will differ

what's oscillating?

The probability $P_\nu(L)$ of seeing flavor e [e.g.] in a beam created as μ : [L in km, E_ν in GeV]

$$P_\nu(L) = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L / E_\nu)$$

depends on two “intrinsic” parameters:

mixing strength $\sin^2 2\theta$

and mass splitting $\Delta m^2 = |m_1^2 - m_2^2|$

and two “experimental” parameters:

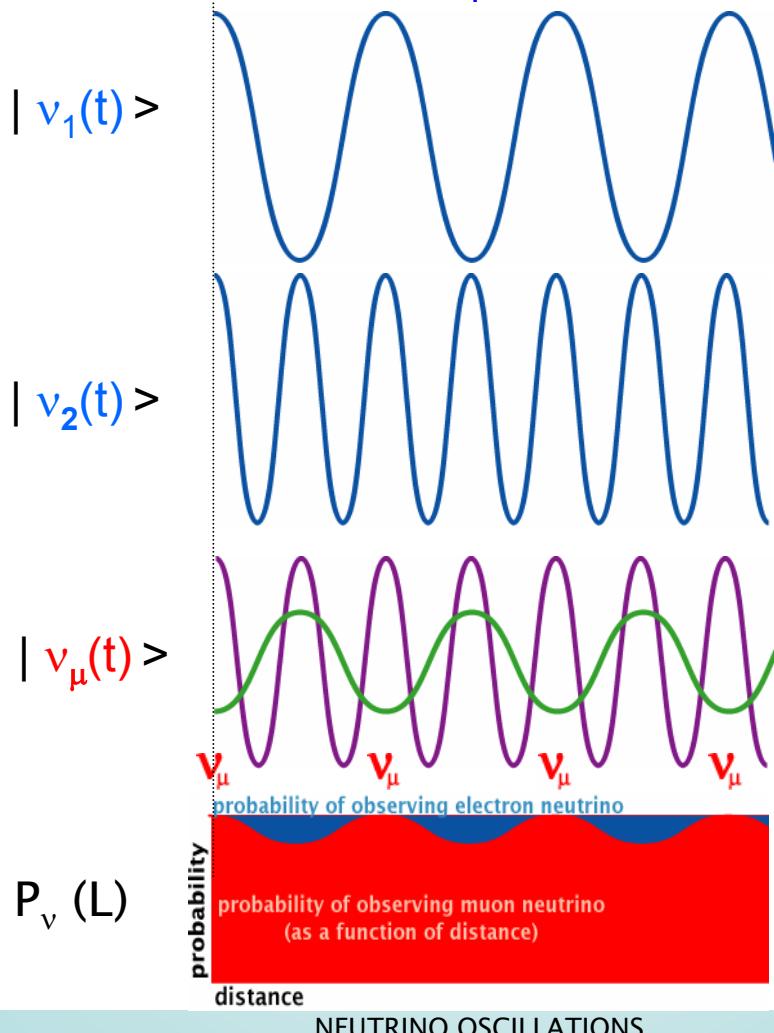
neutrino beam energy E_ν

and source-detector distance L

what's oscillating?

Start with a muon neutrino:

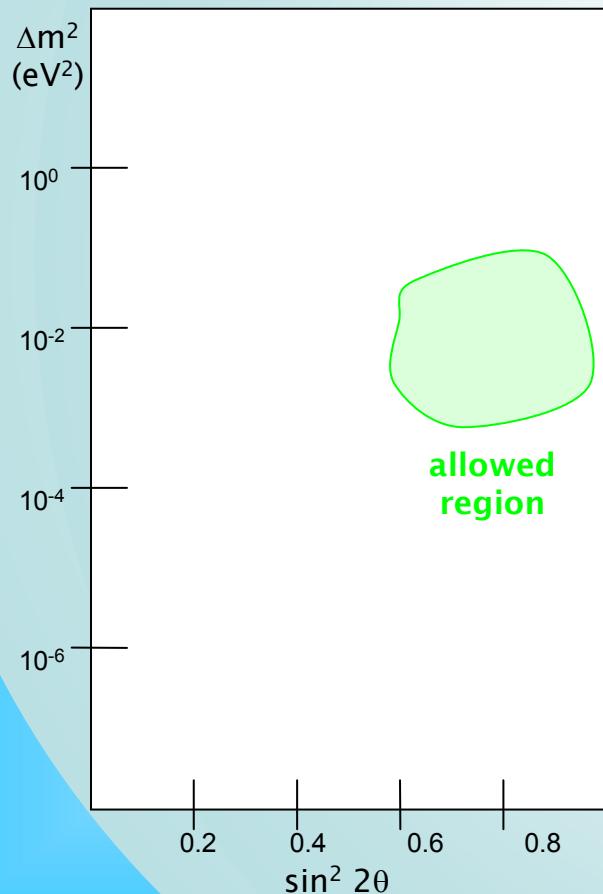
$$| \nu(t=0) \rangle = -\sin \theta | \nu_1 \rangle + \cos \theta | \nu_2 \rangle$$



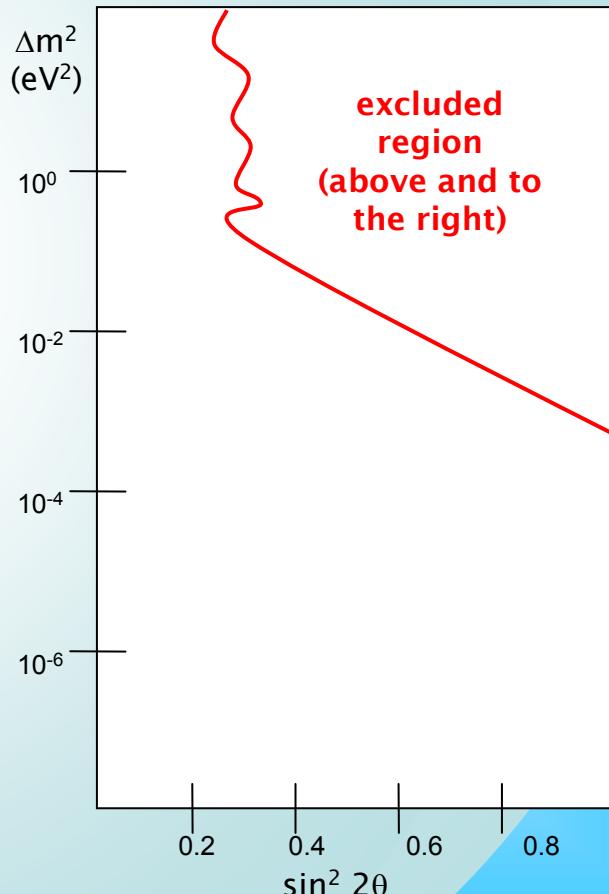
parameter space plots

Each experiment (L, E) makes one measurement (probability),
and so determines a region in (Δm^2 , $\sin^2 2\theta$) space

observation: allowed region no signal: excluded region



NEUTRINO OSCILLATIONS

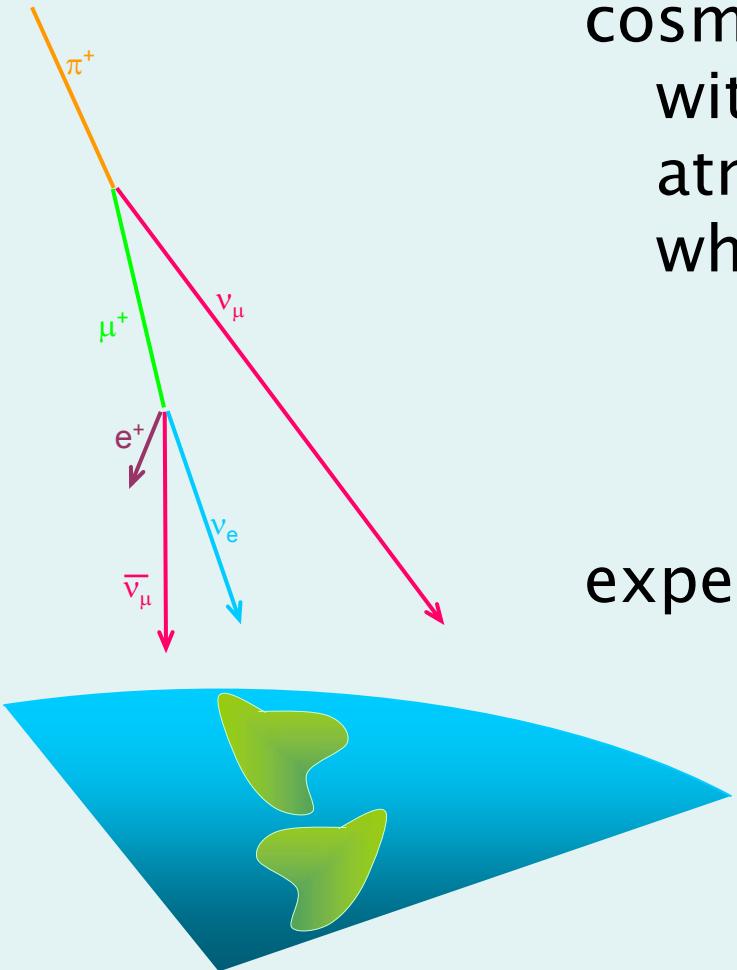


now you see 'em...

- Disappearance experiments
 - Expect event rate R , see $R' < R$
 - Challenge: know neutrino flux
- Appearance experiments
 - Expect events of flavor a, see flavor b
 - Challenge: precise background understanding
- L/E dependence is a key feature

OSCILLATION EVIDENCE I: atmospheric neutrinos

cosmic cascades



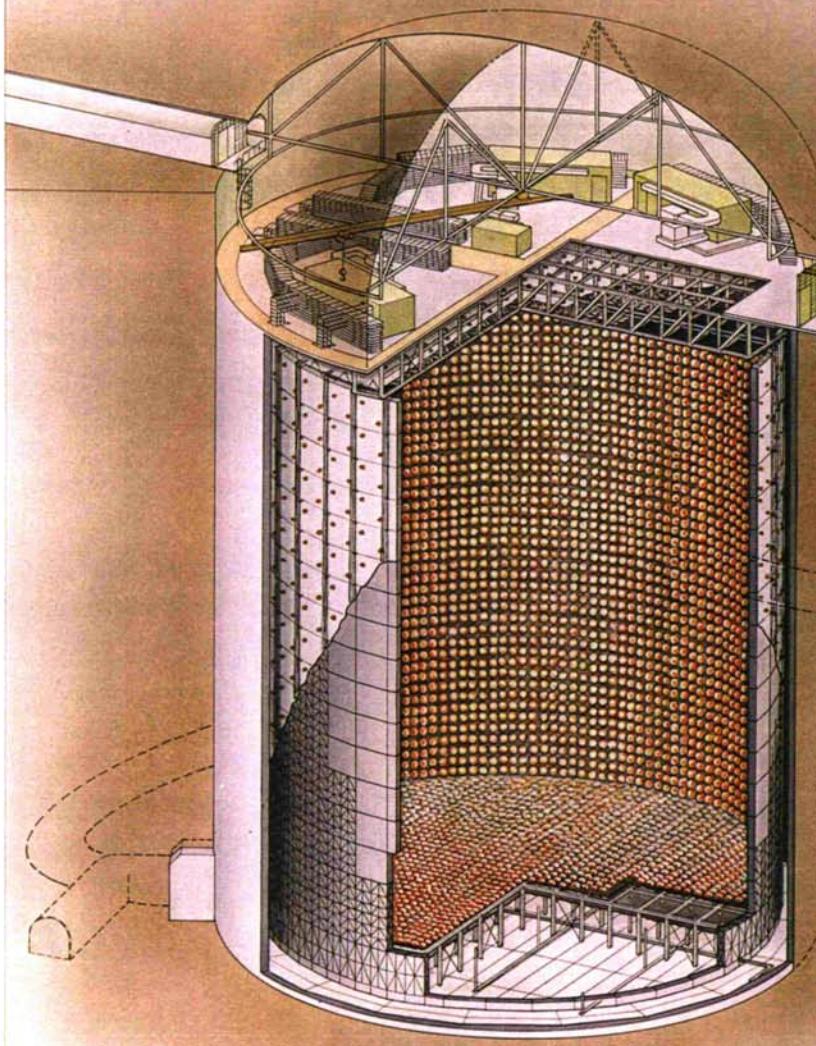
cosmic rays (protons) interact with molecules in the upper atmosphere to make pions, which decay:

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ \nu_\mu \\ &\downarrow e^+ \bar{\nu}_\mu \nu_e\end{aligned}$$

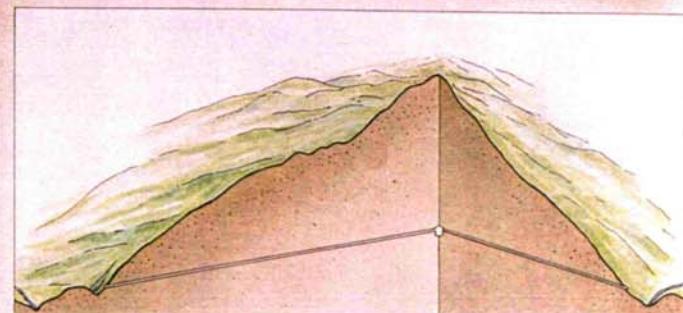
expect ν_μ -like / ν_e -like ratio of 2:1

see event ratio about 1.4:1
(disappearance)

Super-KamiokaNDE

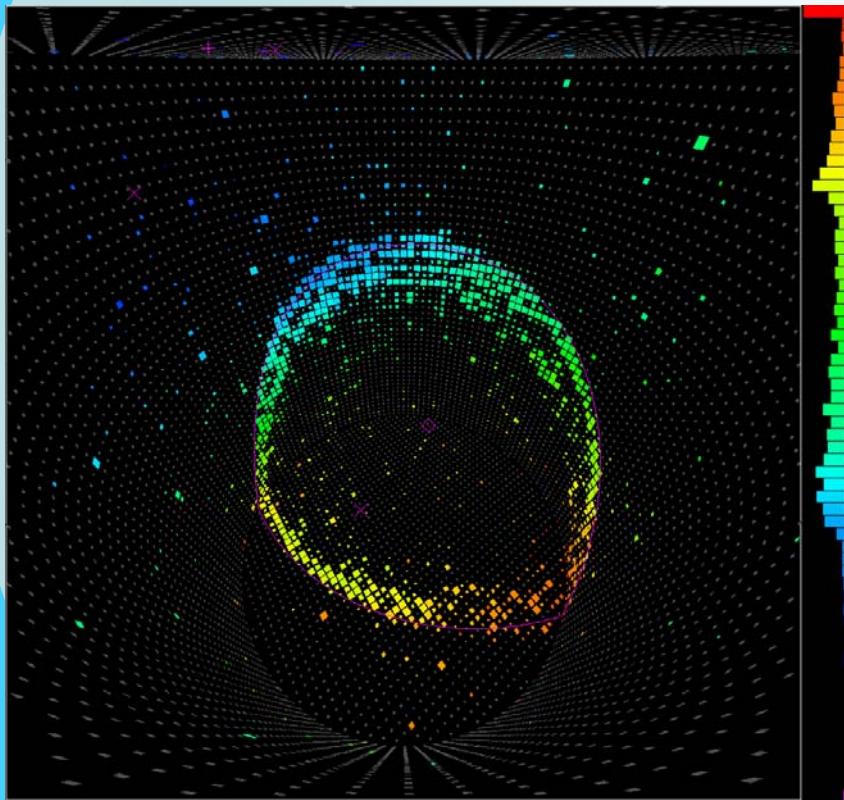


- ◆ water Čerenkov detector
- ◆ 40 m diameter, 40 m tall
- ◆ 50 kilotons of water
- ◆ 11,000 20 inch photomultiplier tubes
- ◆ 1 km underground

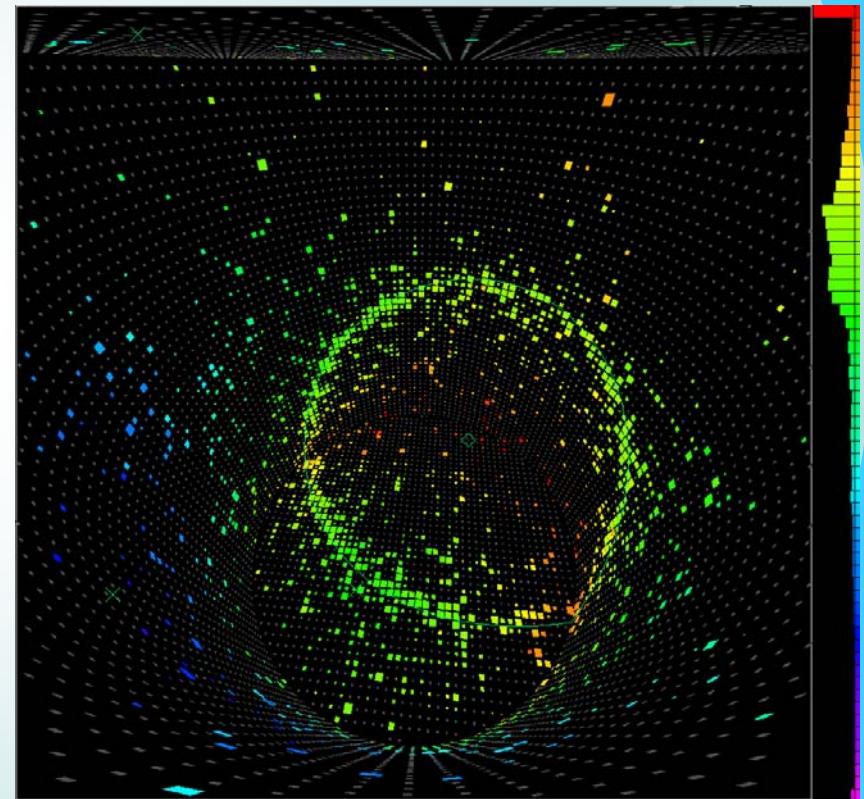


Super-KamiokaNDE

Čerenkov light: cone intersecting wall makes a ring of illuminated PMTs whose pattern → particle ID

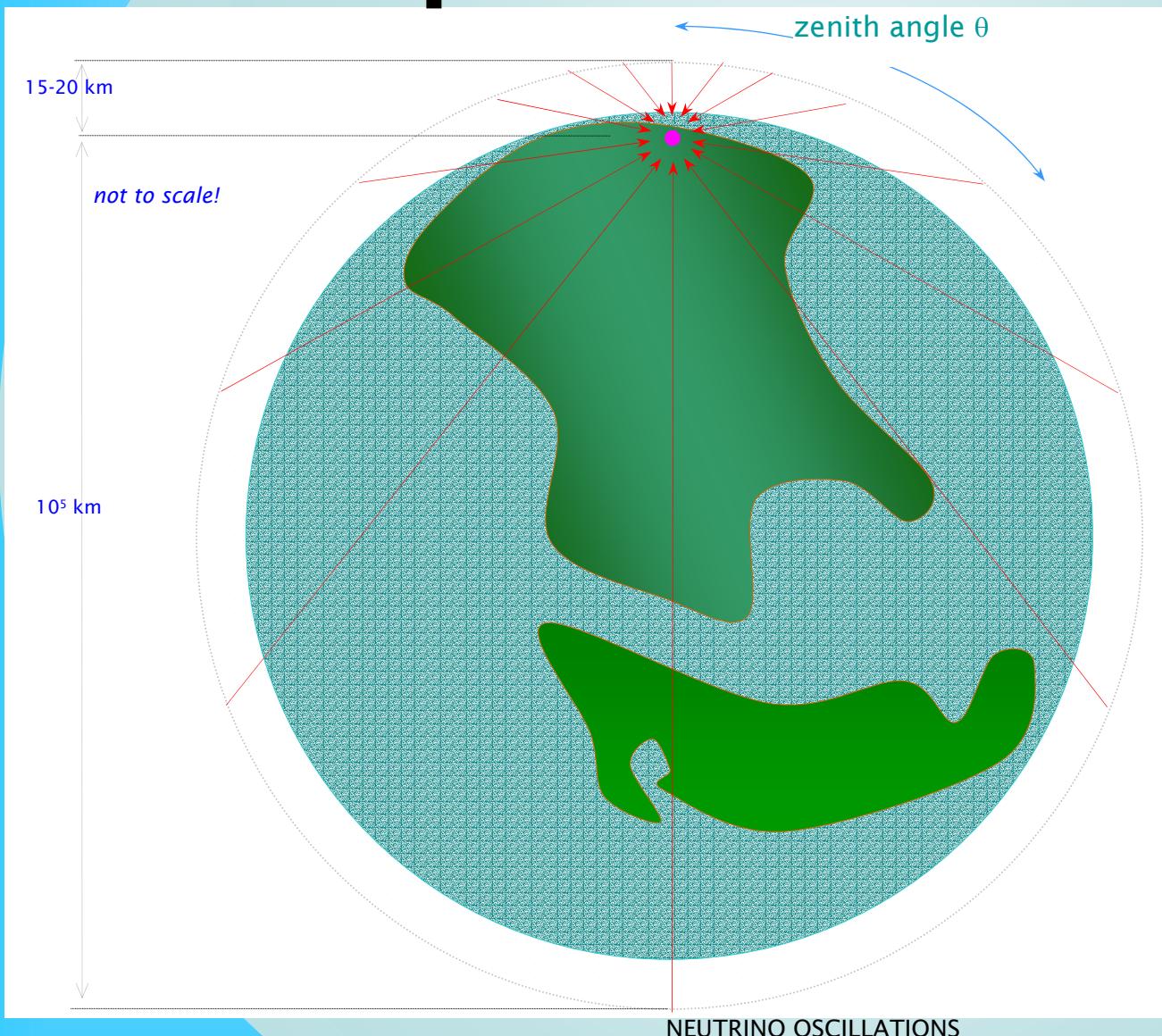


muon: “sharp”



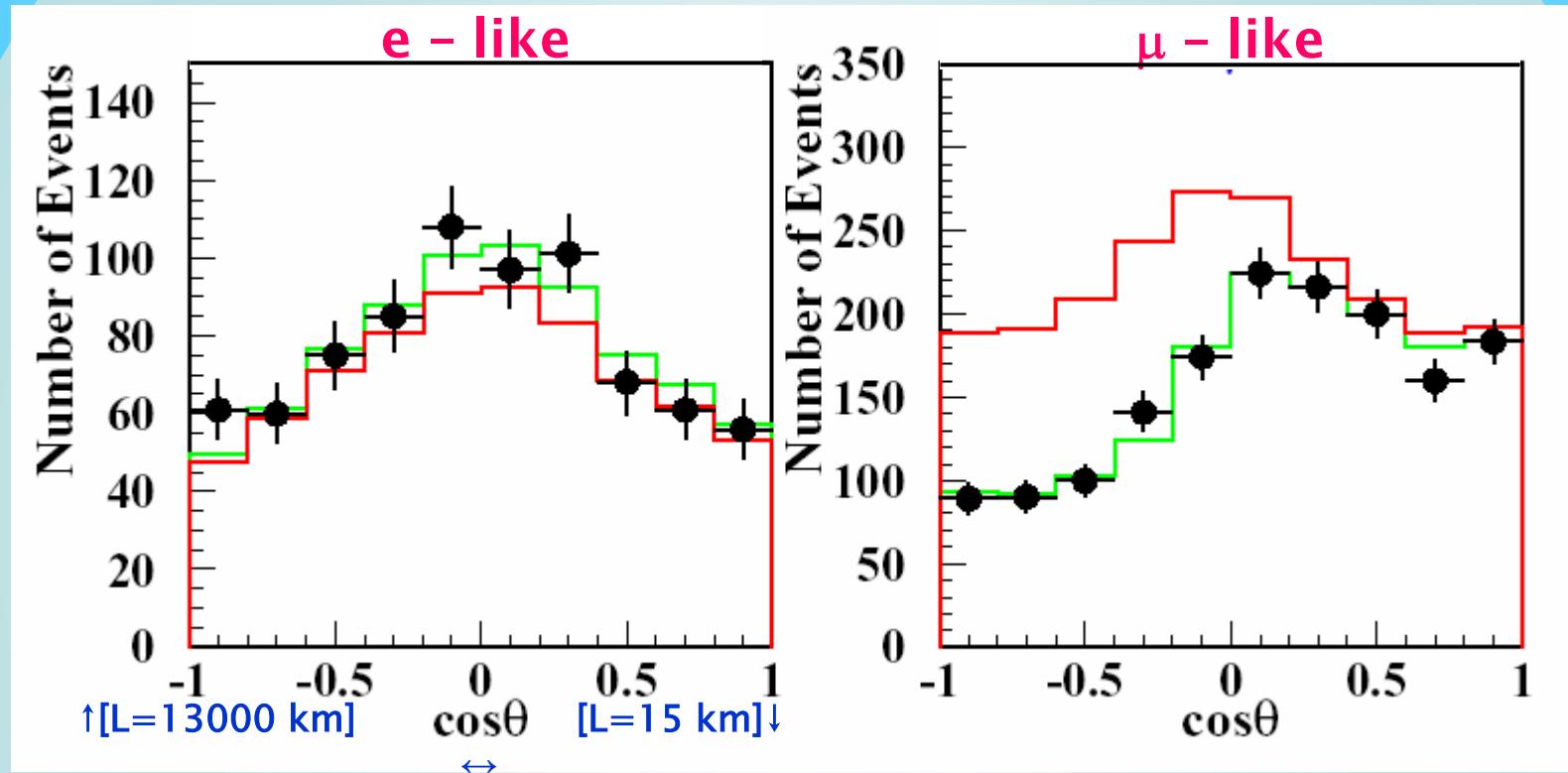
electron “fuzzy”

Super-KamiokaNDE



zenith angle
dependence:
changing θ
changes L

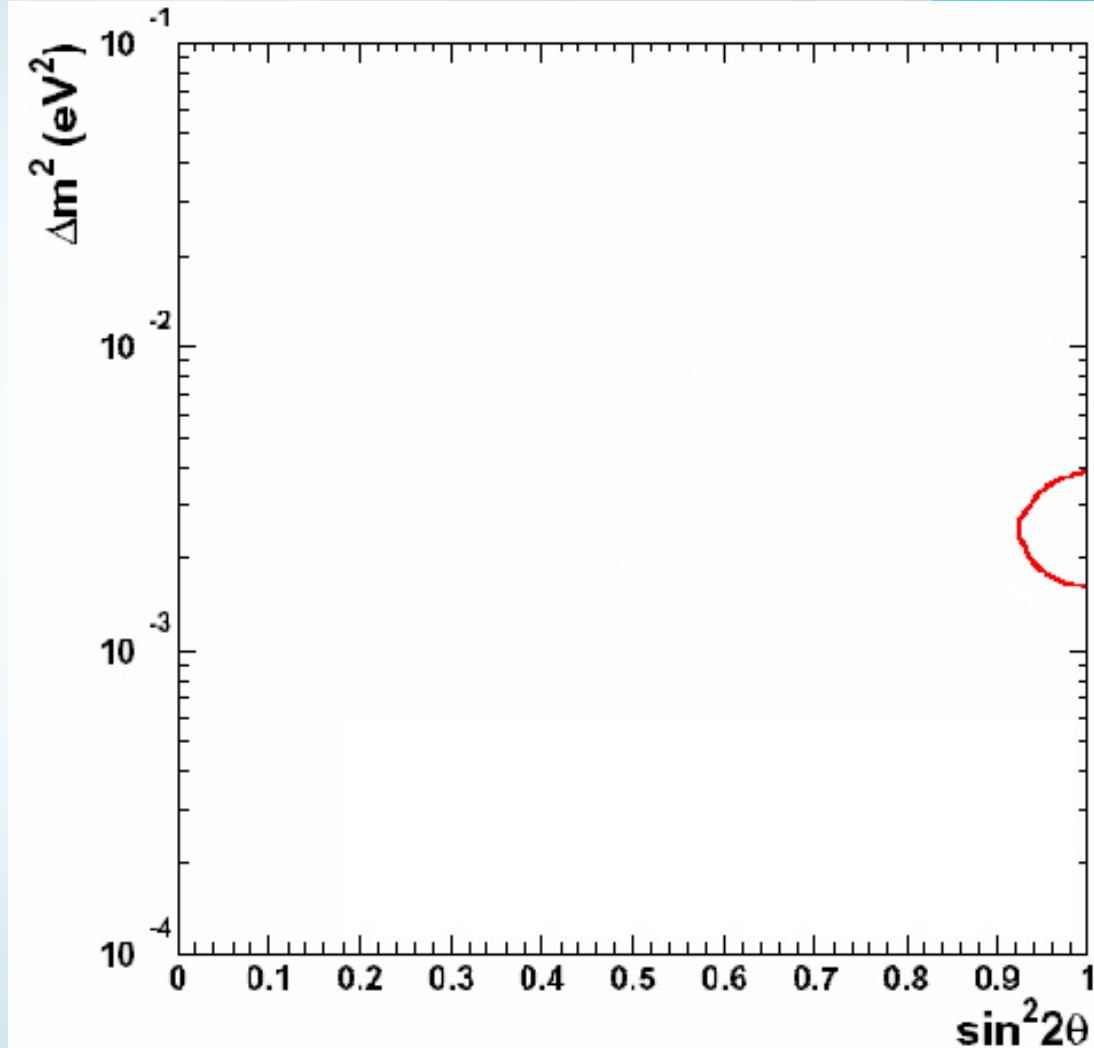
zenith angle distributions: e-like vs. μ -like



- black: data; red: no oscillation; green: oscillation with $\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$
- observed deficit in upward-going muons, NOT seen with electrons

Super-Kamiokande parameter space

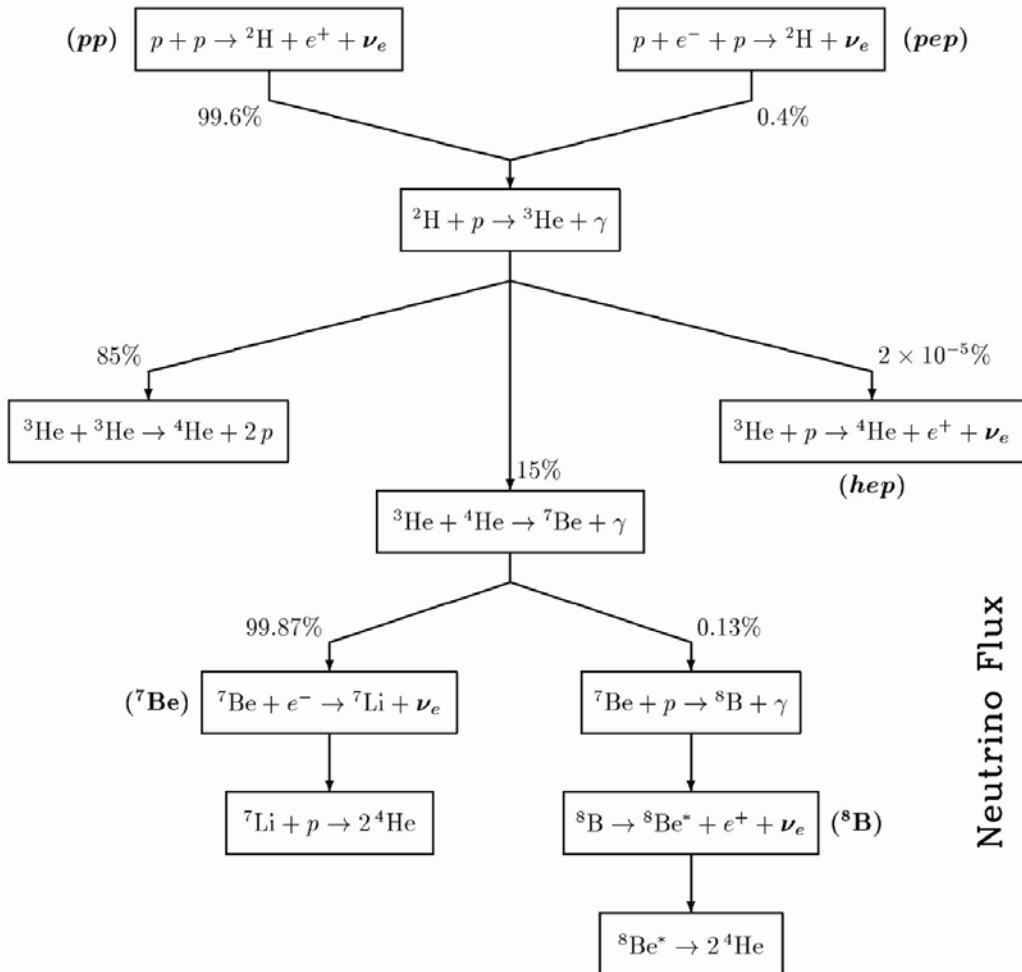
- analysis favors oscillation $\nu_\mu \rightarrow \nu_\tau$
- $E = 0.5 - 3 \text{ GeV}$
- $L = 15 - 13000 \text{ km}$
- best fit:
 $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$
 $\sin^2 2\theta = 1.0$



OSCILLATION EVIDENCE II: solar neutrinos

NEUTRINO OSCILLATIONS

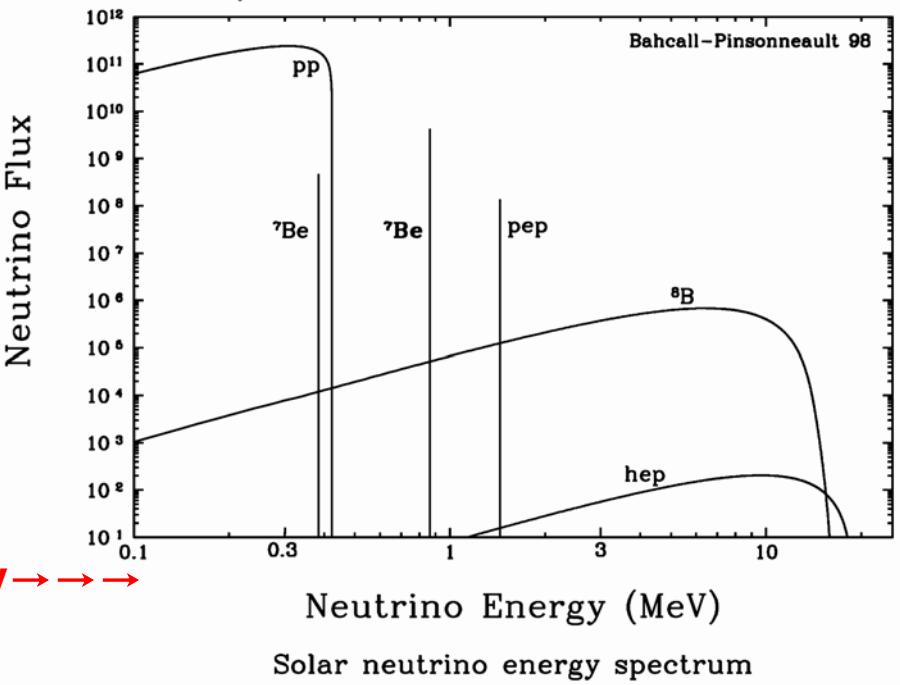
neutrinos from the Sun



Detection depends on energy:



$\nu e^- \rightarrow \nu e^-$ (ν_e NC, CC; ν_μ/ν_τ NC)
(water Čerenkov)



Note LOW neutrino energy →→→

another deficit...

- earliest experiment:
Davis at Homestake (Cl): 1/3 expected rate
- Super-K (H_2O): about 1/2 of expected rate
- SAGE/GALLEX: 60 – 70% expected rate
- Standard Solar Model (SSM) unlikely to be wrong – supported by other observations
- Oscillations? Maybe, but to what?
- problems: Ga/Cl can't see ν_μ , ν_τ
 H_2O can't distinguish flavors

Sudbury Neutrino Observatory (SNO)

- 12 m diameter central sphere holds 1 kton heavy water (D_2O) [$\check{\text{C}}\text{erenkov}$]
- deuterium: measure number of neutrinos (flux) from 8B reaction

CC: $\nu_e d \rightarrow e^- p p$

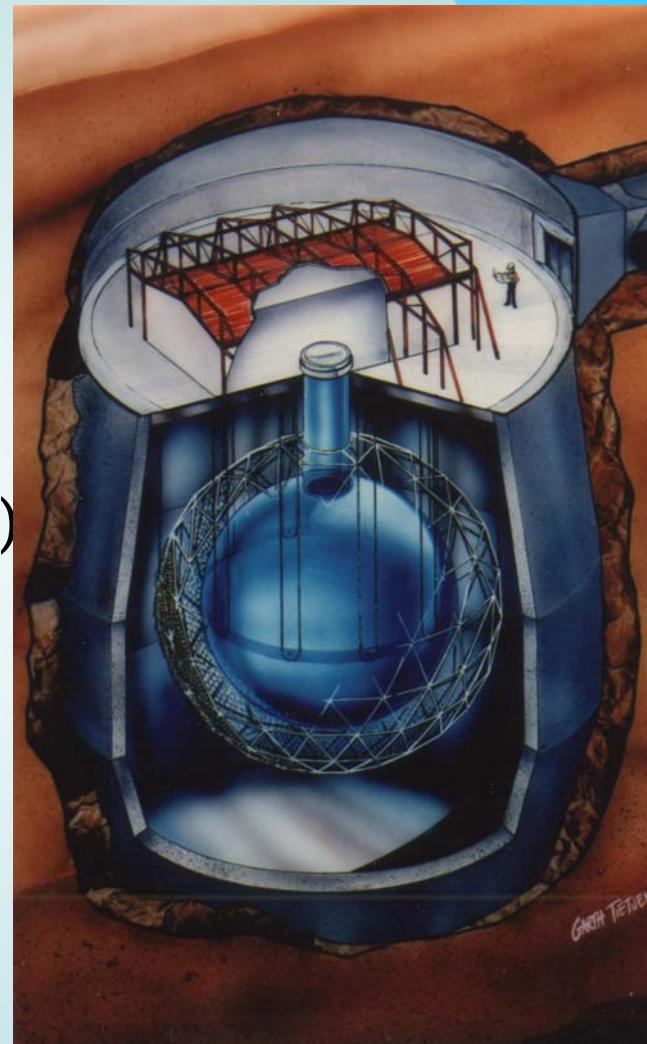
- E_{electron} measures E_ν (spectrum)
- flavor specific: ONLY ν_e flux

NC: $\nu_x d \rightarrow \nu_x n p$

- measures $\nu_e + \nu_\mu + \nu_\tau$ flux

ES: $\nu_x e^- \rightarrow \nu_x e^-$

- highly directional: ☺
- CC/NC for ν_e , NC for ν_μ / ν_τ



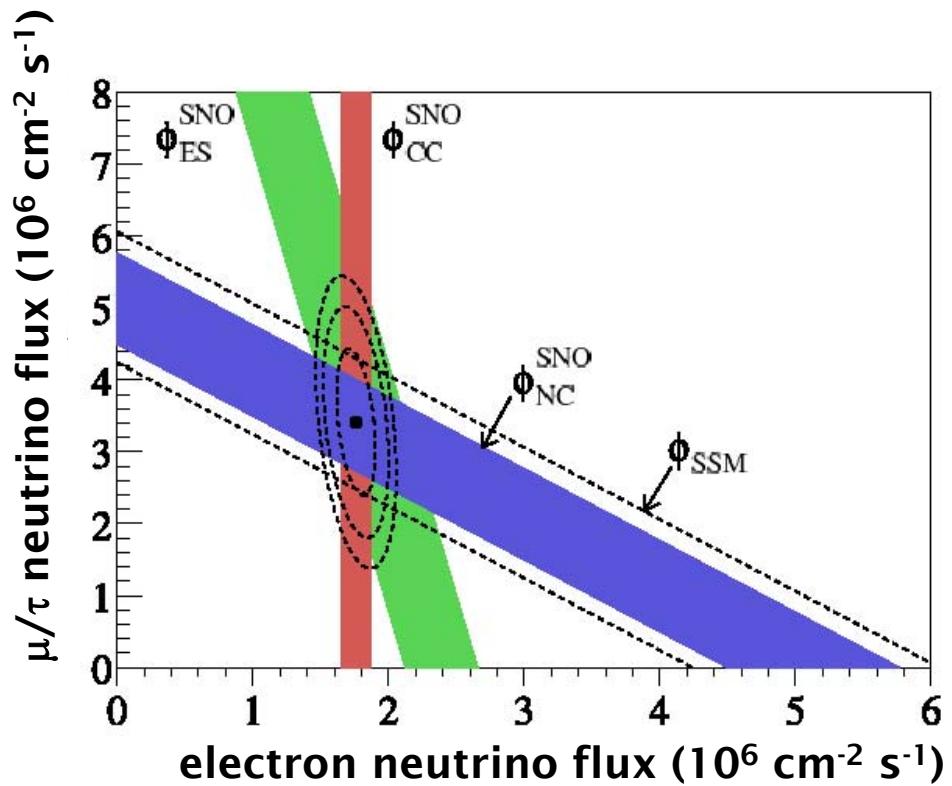
Sudbury Neutrino Observatory (SNO)

RESULTS!

- NC, CC, ES signals allow first separable determination of the number of electron neutrinos and non-electron neutrinos from solar ${}^8\text{B}$ reaction
- CC measure of ν_e s: 1/3 Standard Solar Model prediction
- **BUT** NC (measures $\nu_{e+\mu+\tau}$) measurement agrees with SSM prediction within errors
- FIRST definitive measure of μ/τ neutrinos from Sun
- confirms theoretical prediction of fusion processes at solar interior

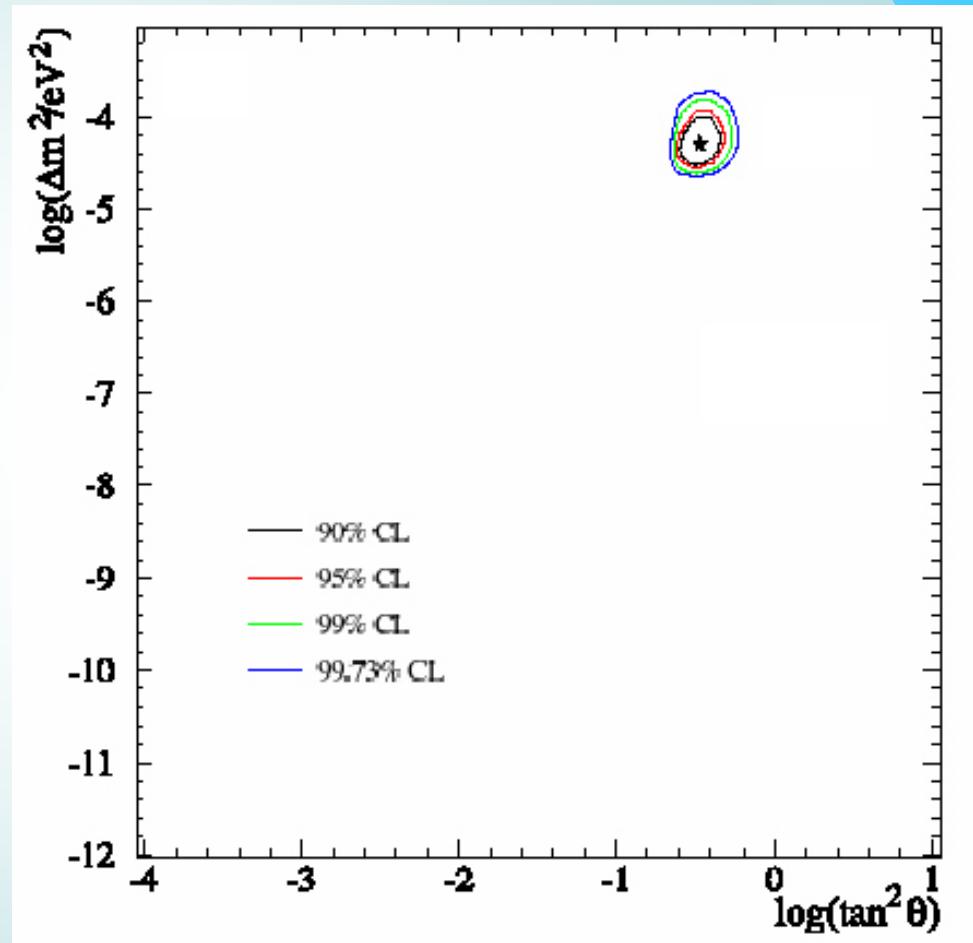
neutrino flux results

- CC flux: no μ/τ dependence
- NC flux: total = $e + \mu/\tau$
- ES flux: mostly from e, some μ/τ dependence
- SSM flux prediction



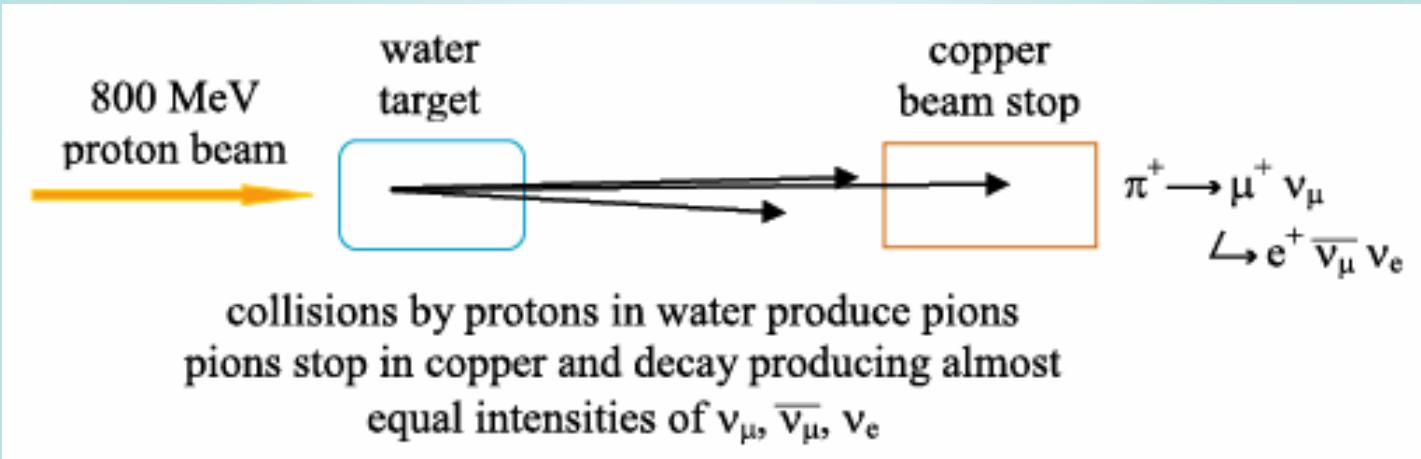
SNO parameter space

- Oscillation of $\nu_e \rightarrow \nu_{\mu/\tau}$
- E: 3-10 MeV
- L: 1.5×10^8 km
- large mixing angle (LMA) best fit:
 $\Delta m^2 = 5.0 \times 10^{-5} \text{ eV}^2$
 $\sin^2 2\theta = 0.76$



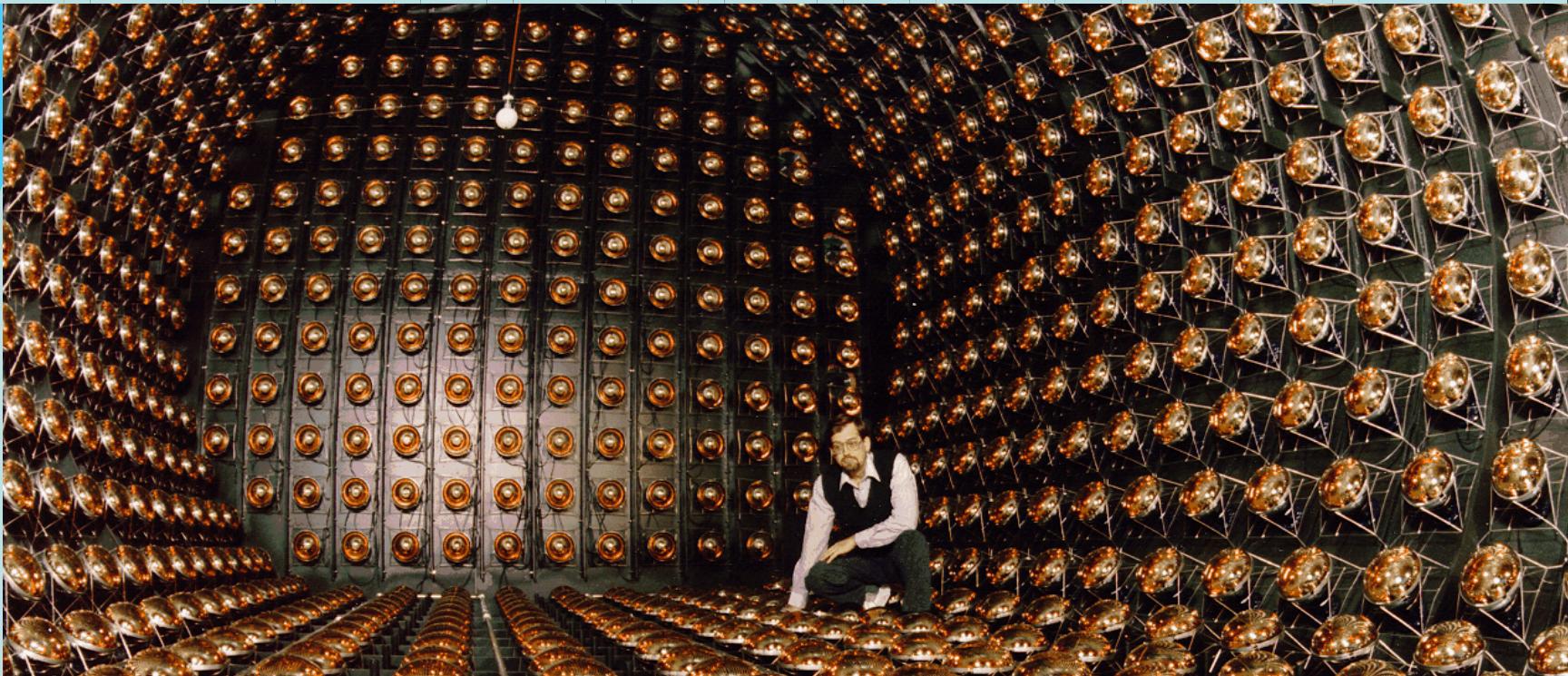
OSCILLATION EVIDENCE III: accelerator neutrinos

LSND: beam



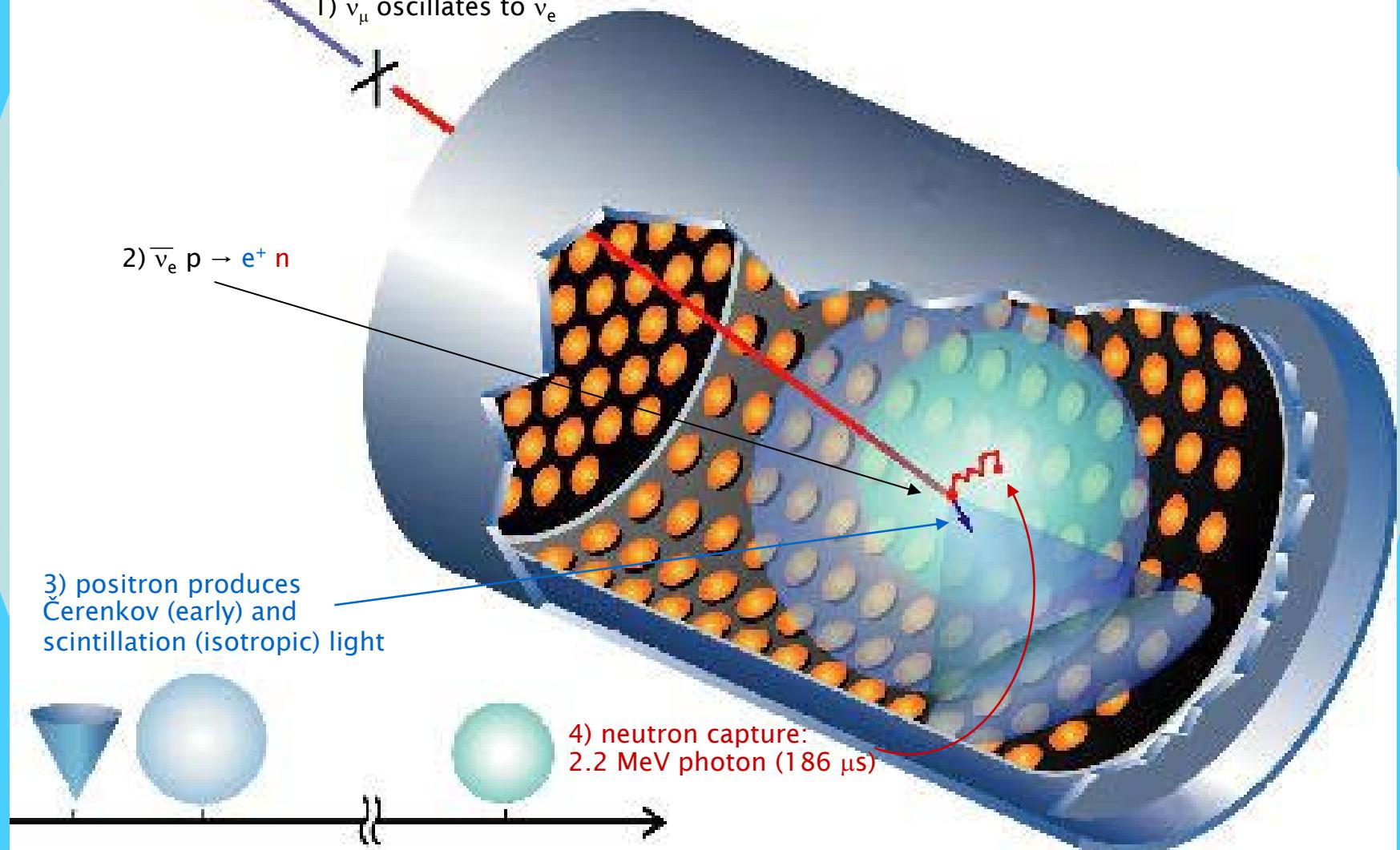
- neutrino production: end of pion decay chain
(just as in atmospheric case)
- note that decay chain of positive pions does NOT include electron antineutrinos
- neutrinos travel 30 m downstream to detector
- high intensity beam: 29 kC of protons targeted

LSND: detector



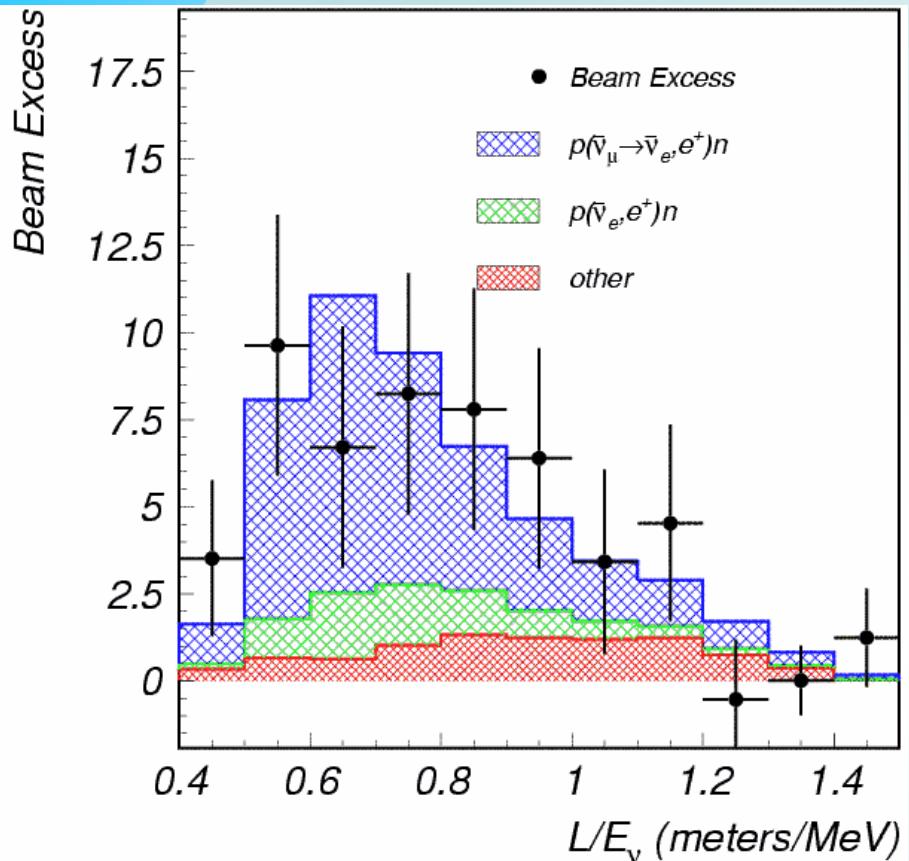
- cylinder (5.5 m diameter, 8.5 m long)
- 167 tons of mineral oil
- doped to give both Čerenkov and scintillation light
- 1 220 photomultiplier tubes

LSND: signal



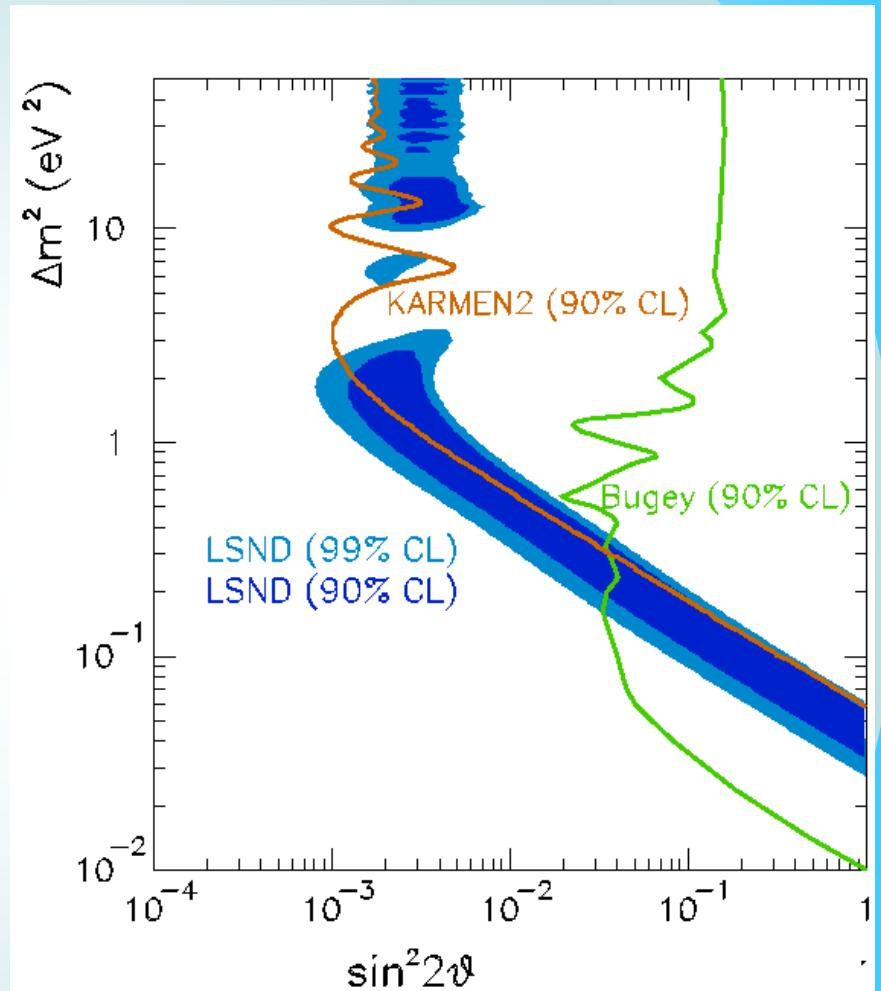
NEUTRINO OSCILLATIONS

LSND: result/parameter space



excess (above background):
 $87.9 \pm 22.4 \pm 6.0$ events

>>> first APPEARANCE result



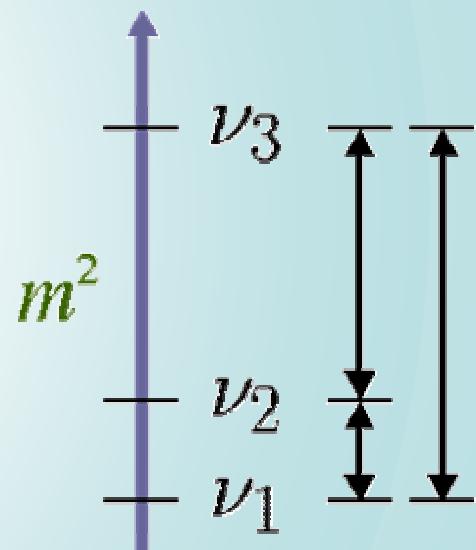
E: 30 MeV ; L = 30 m
 best fit $\Delta m^2 = 1.2$ eV 2

The case of the inconsistent Δm^2 s

- know (from Z boson studies):
3 neutrino flavors; entails
only 2 independent Δm^2

$$\Delta m_{31}^2 = \Delta m_{21}^2 + \Delta m_{32}^2$$

- atmospheric : $2.5 \times 10^{-3} \text{ eV}^2$
- solar : $5.0 \times 10^{-5} \text{ eV}^2$
- LSND : 1.2 eV^2



The case of the inconsistent Δm^2 s

What are the options?

- One (or more) of the experiments is not seeing oscillations?
- There's a fourth ("sterile") neutrino that doesn't participate in the standard weak interaction (doesn't "talk" to the Z boson)??
- Other new physics???
- **LSND result needs further testing...**

MiniBooNE at Fermilab

NEUTRINO OSCILLATIONS

The BooNE Collaboration

University of Alabama:	Y.Liu, I.Stancu
Bucknell University:	S.Koutsoliotas
University of California, Riverside:	E.Church, C.Green, G.J.VanDalen
University of Cincinnati:	E.Hawker, R.A.Johnson, J.L.Raaf
University of Colorado:	T.Hart, E.D.Zimmerman
Columbia University:	L.Bugel, J.M.Conrad, J.Formaggio, J.Link, J.Monroe, M.H.Shaevitz, M.Sorel, G.P.Zeller
Embry Riddle Aeronautical University:	D.Smith
Fermi National Accelerator Laboratory:	L.Bartoszek, C.Bhat, S.J.Brice, B.C.Brown, D.A.Finley, B.T.Fleming, R.Ford, F.G.Garcia, P.Kasper, T.Kobilarcik, I.Kourbanis, A.Malensek, W.Marsh, P.Martin, F.Mills, C.Moore, P.Nienaber, E.Prebys, A.D.Russell, P.Spentzouris, R.Stefanski, T.Williams D.C.Cox, J.A.Green, H.Meyer, R.Tayloe
Indiana University: Los Alamos National Laboratory:	G.T.Garvey, W.C.Louis, G.McGregor, S.McKenney, G.B.Mills, E.Quealy, V.Sandberg, B.Sapp, R.Schirato, R.Van de Water, D.H.White
Louisiana State University:	R.Imlay, W.Metcalf, M.Sung, M.O.Wascko
University of Michigan:	J.Cao, Y.Liu, B.P.Roe
Princeton University:	A.O.Bazarko, P.D.Meyers, R.B.Patterson, F.C.Shoemaker, H.A.Tanaka

The BooNE Collaboration



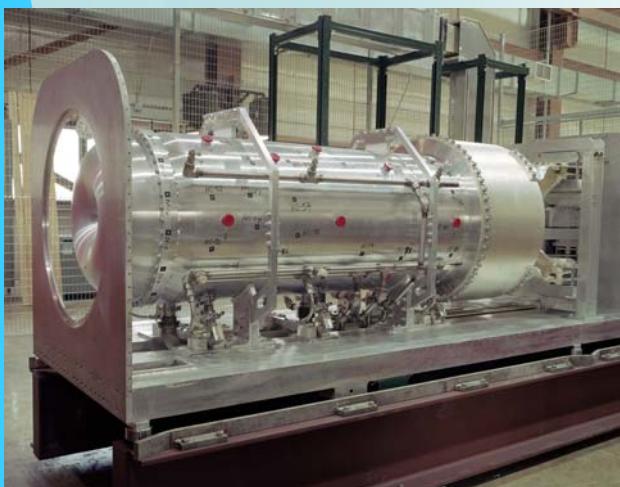
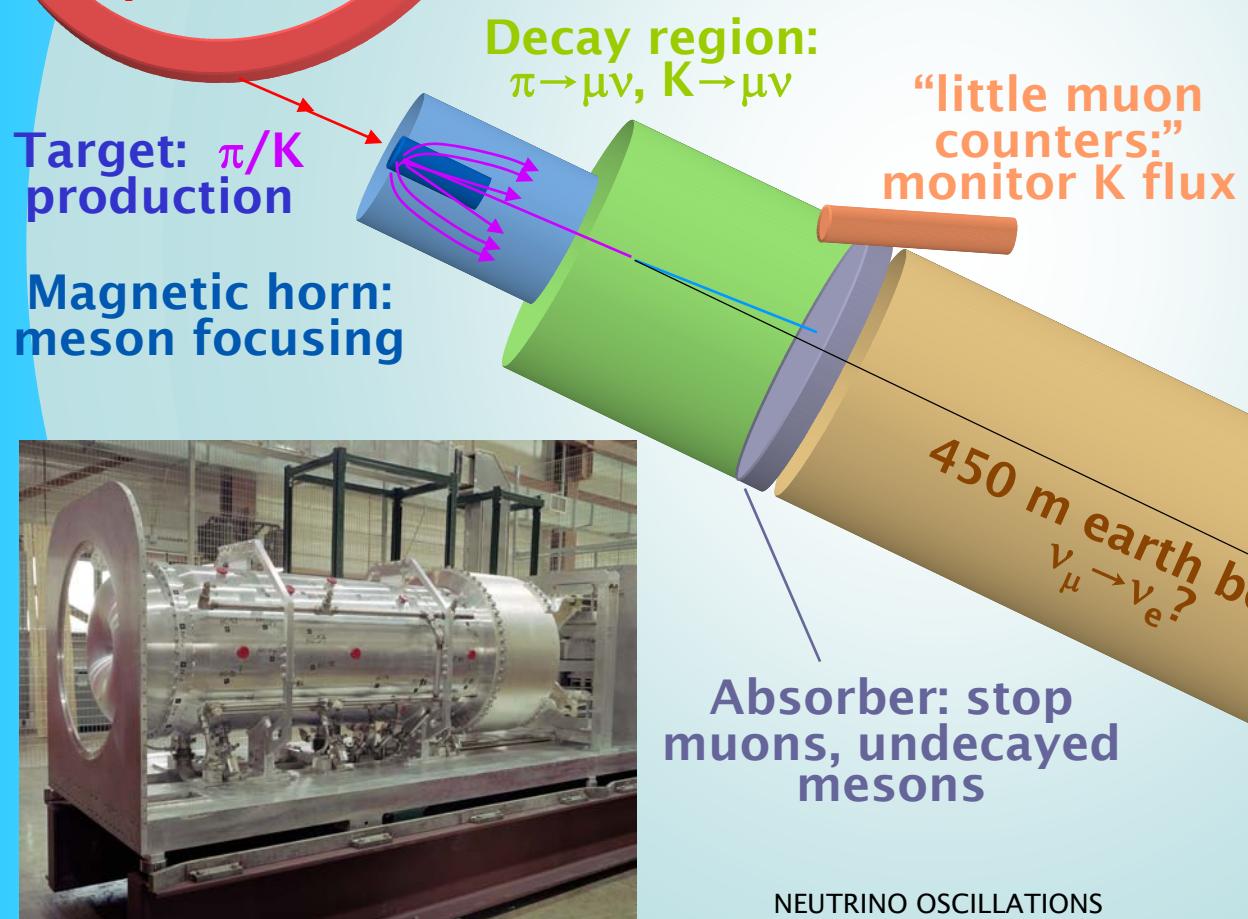
E: 500 MeV;

L = 500 m

L/E same as LSND

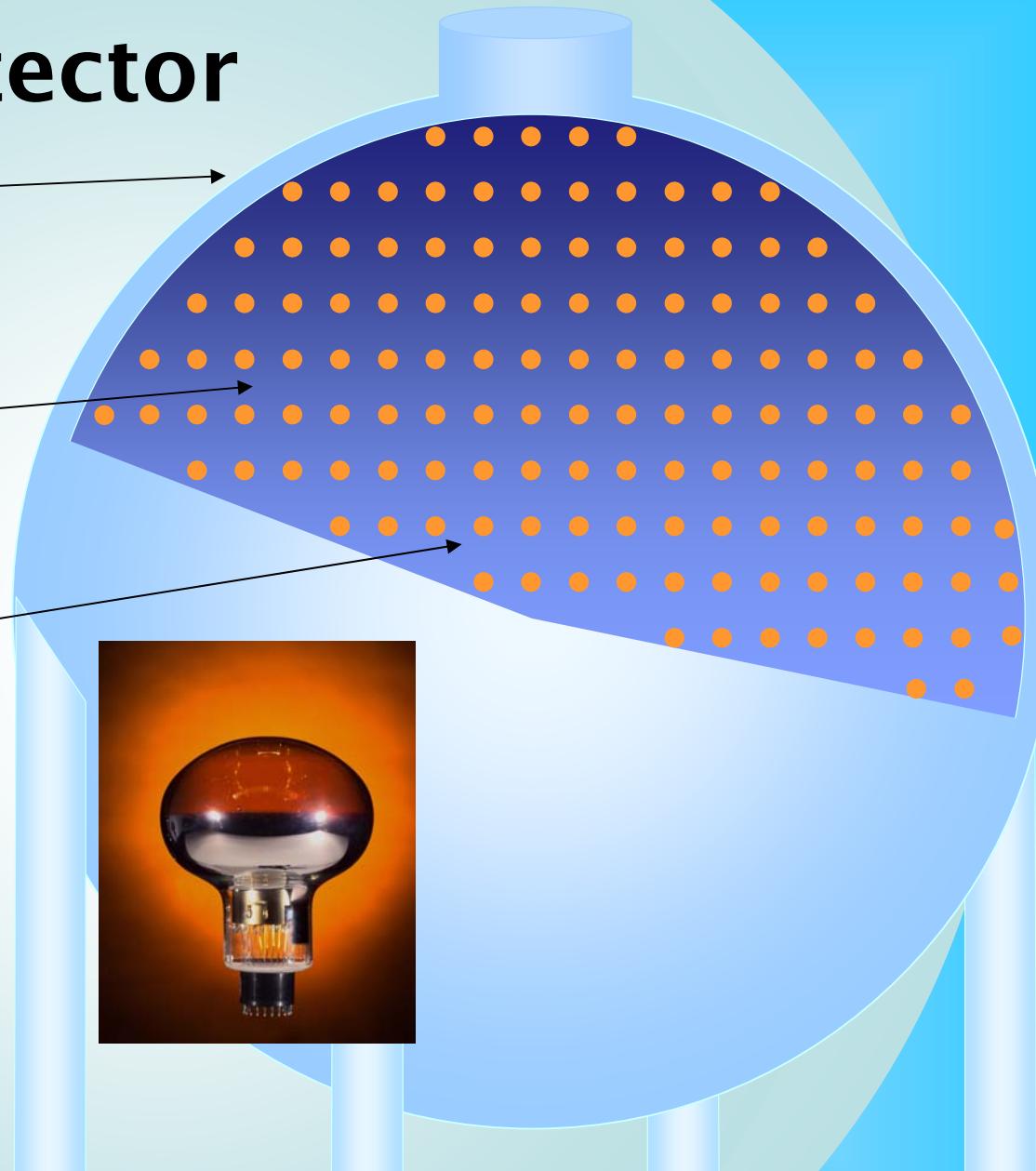


Booster: start
with 8 GeV
protons

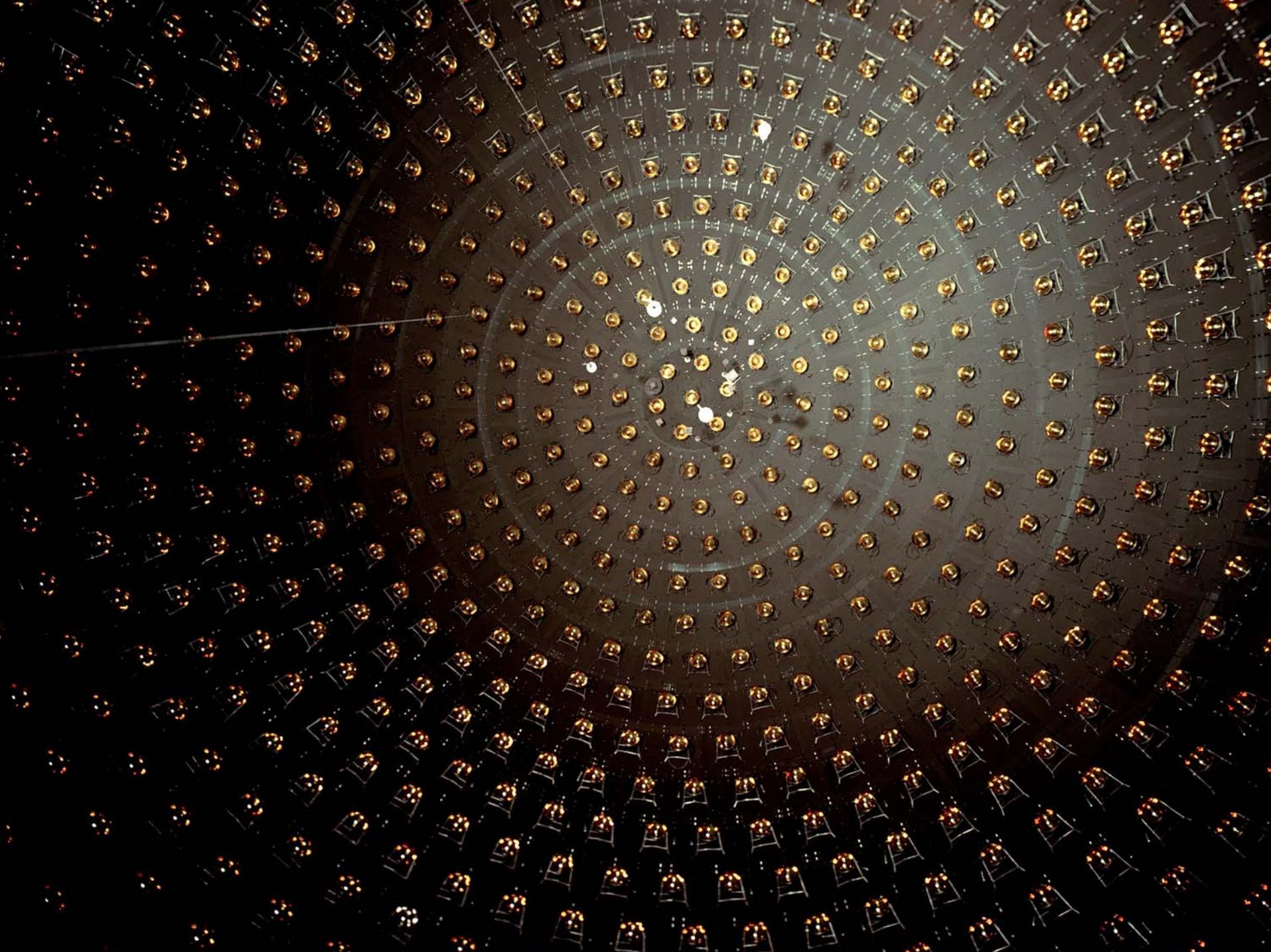


MiniBooNE detector

- 12 m diameter tank
- 800 tons ultra-pure mineral oil
- 1500 8" photo-multiplier tubes
(1300 main tank,
200 veto region)

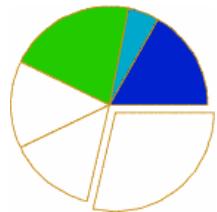
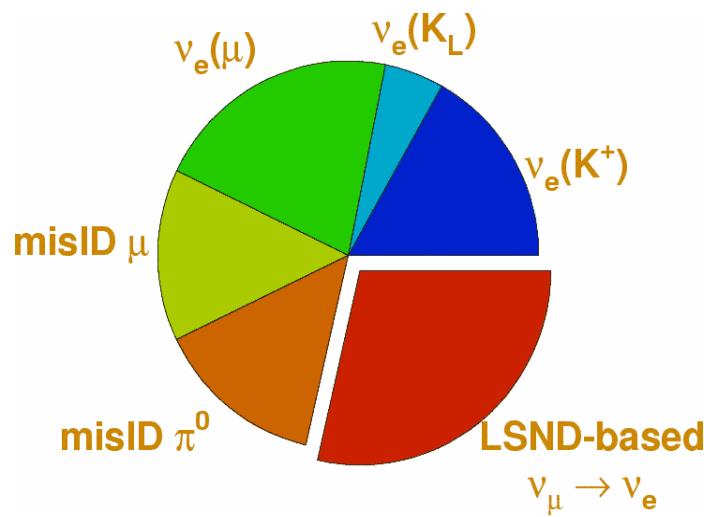


NEUTRINO OSCILLATIONS



signal & backgrounds

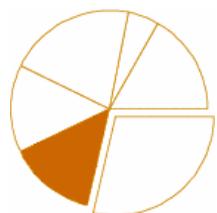
- For 10^{21} protons on target, 500k CC ν_μ events:



Intrinsic ν_e background:
1,500 events



μ mis-ID background:
500 events



π^0 mis-ID background:
500 events

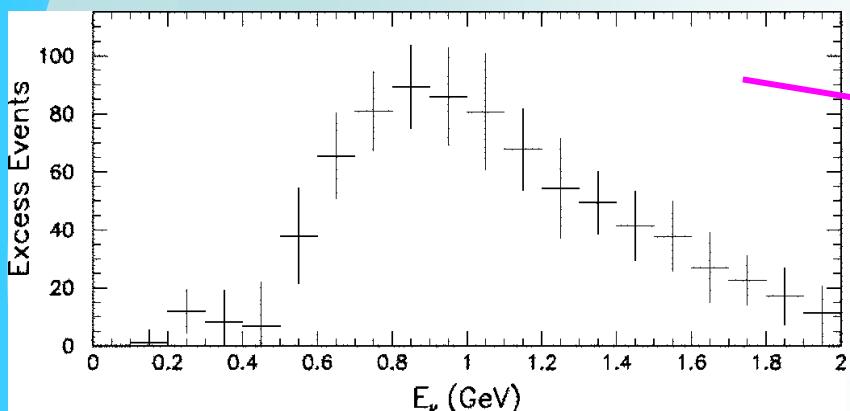


LSND-based $\nu_\mu \rightarrow \nu_e$:
1,000 events

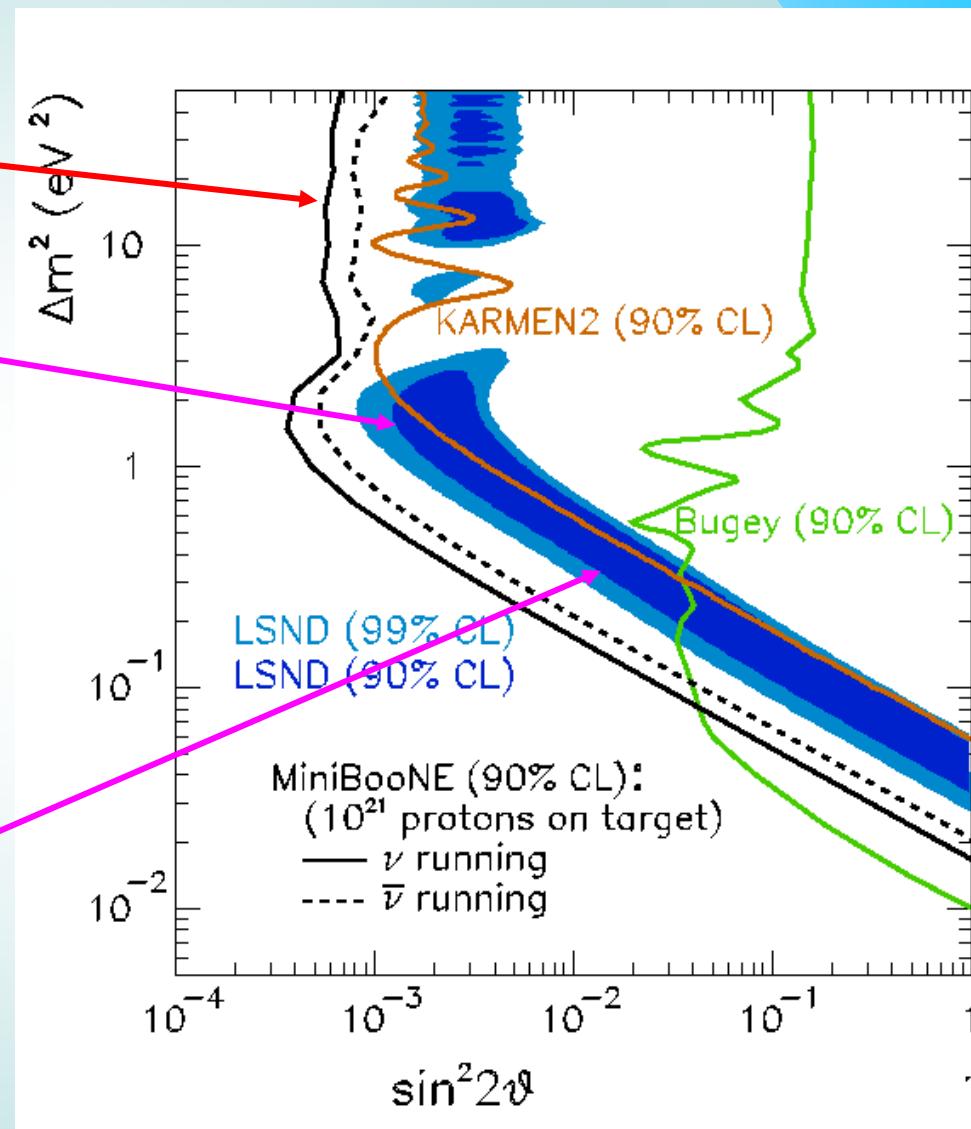
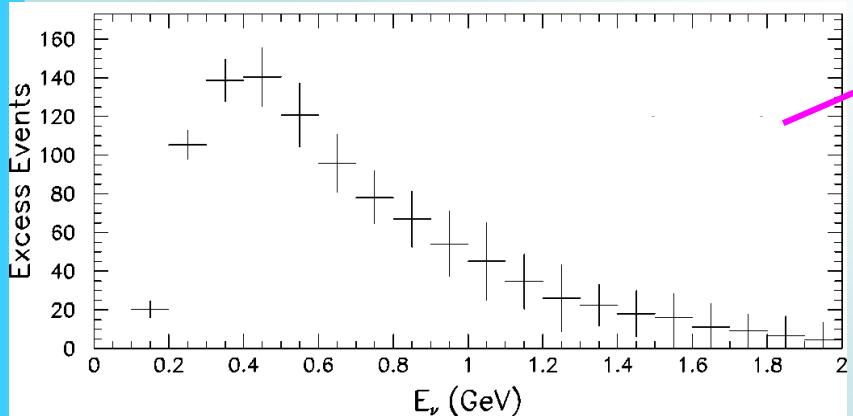
expected sensitivity: 10^{21} p.o.t.

no signal exclusion region

$$\sin^2 2\theta = 0.002, \Delta m^2 = 2.0 \text{ eV}^2$$



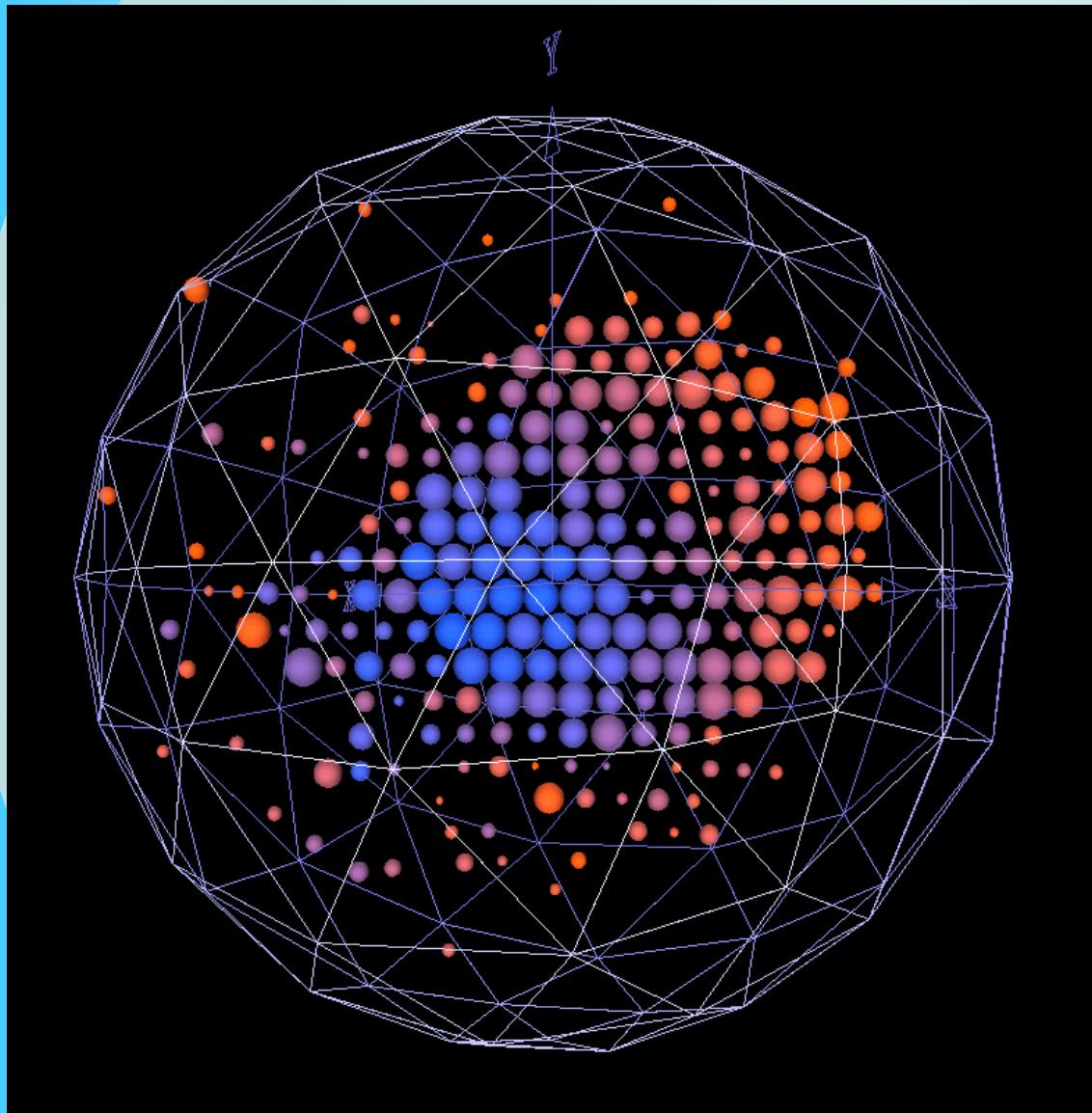
$$\sin^2 2\theta = 0.03, \Delta m^2 = 0.3 \text{ eV}^2$$



Events

size of dot \propto charge
color: time

first μ candidate

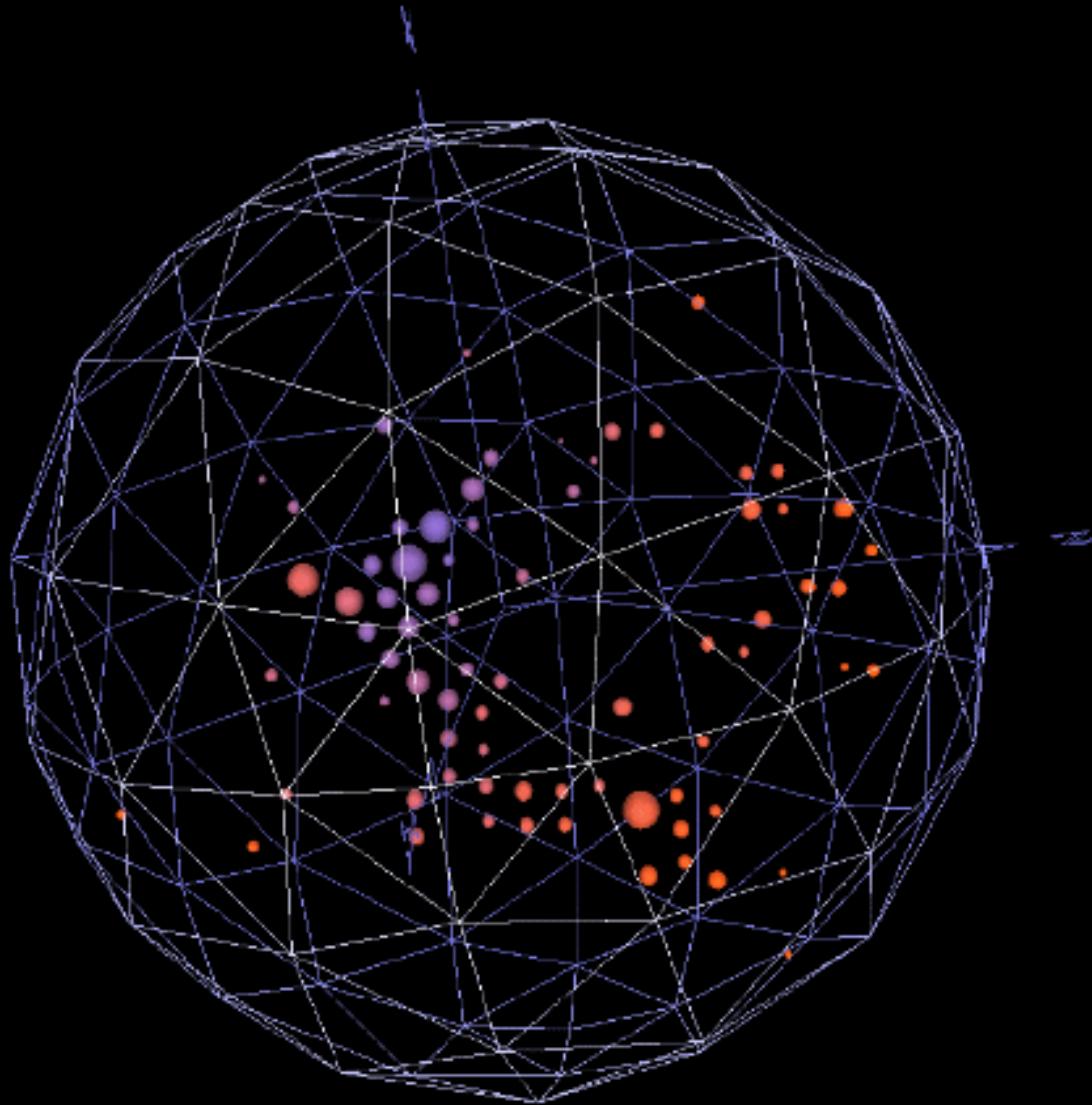


NEUTRINO OSCILLATIONS

Events

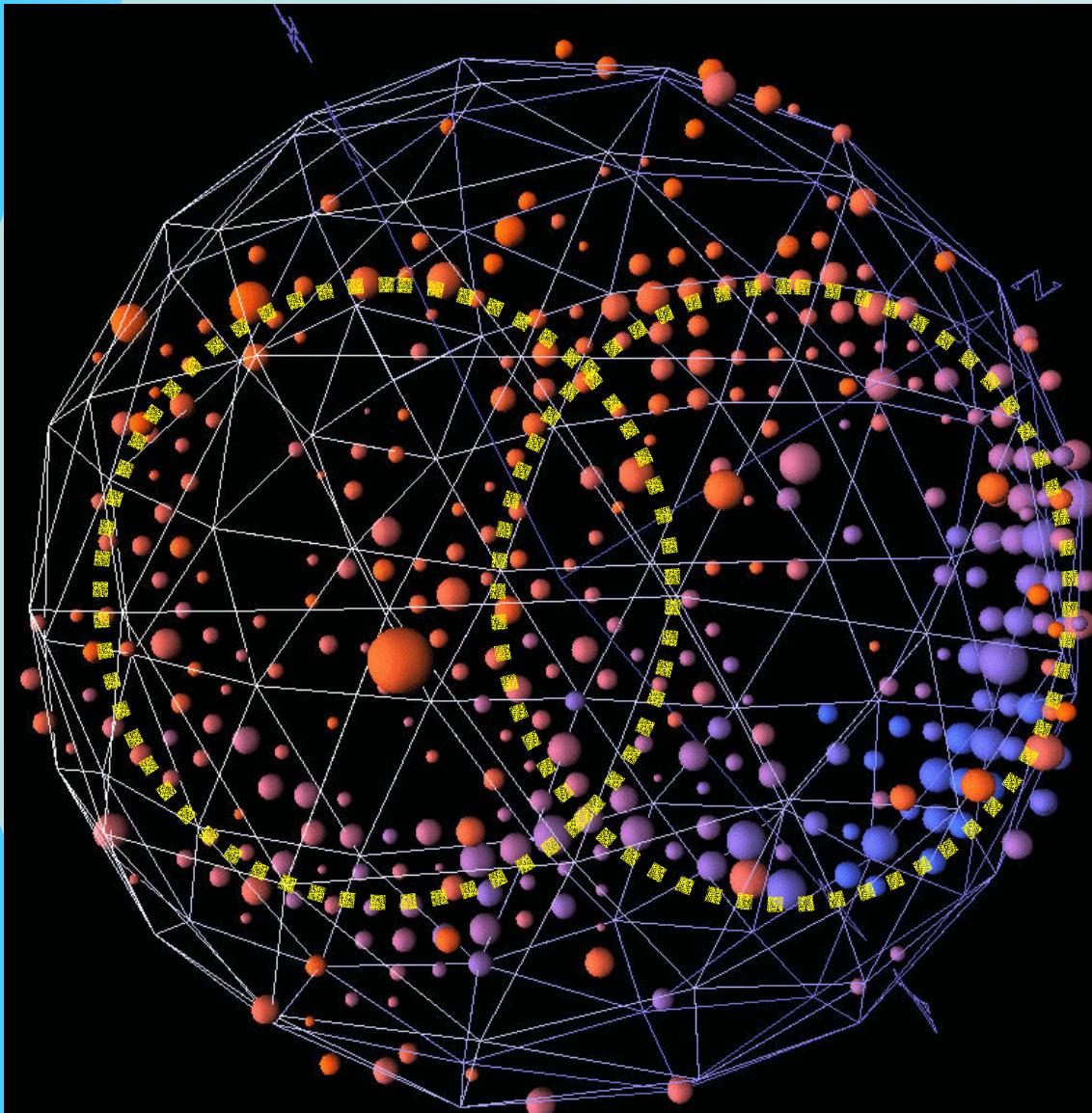
size of dot \propto charge
color: time

Michel (electron from muon decay) candidate



Events

size of dot \propto charge
color: time



$\pi^0 \rightarrow \gamma \gamma$ candidate
(two rings)

NEUTRINO OSCILLATIONS

Detector, calibration, etc. working well: two-ring mass plot

■ Reconstructed $\gamma\gamma$ mass: π^0 peak

$$m_{\pi^0}^2 = 2 E_1 E_2 (1 - \cos \theta_{12})$$

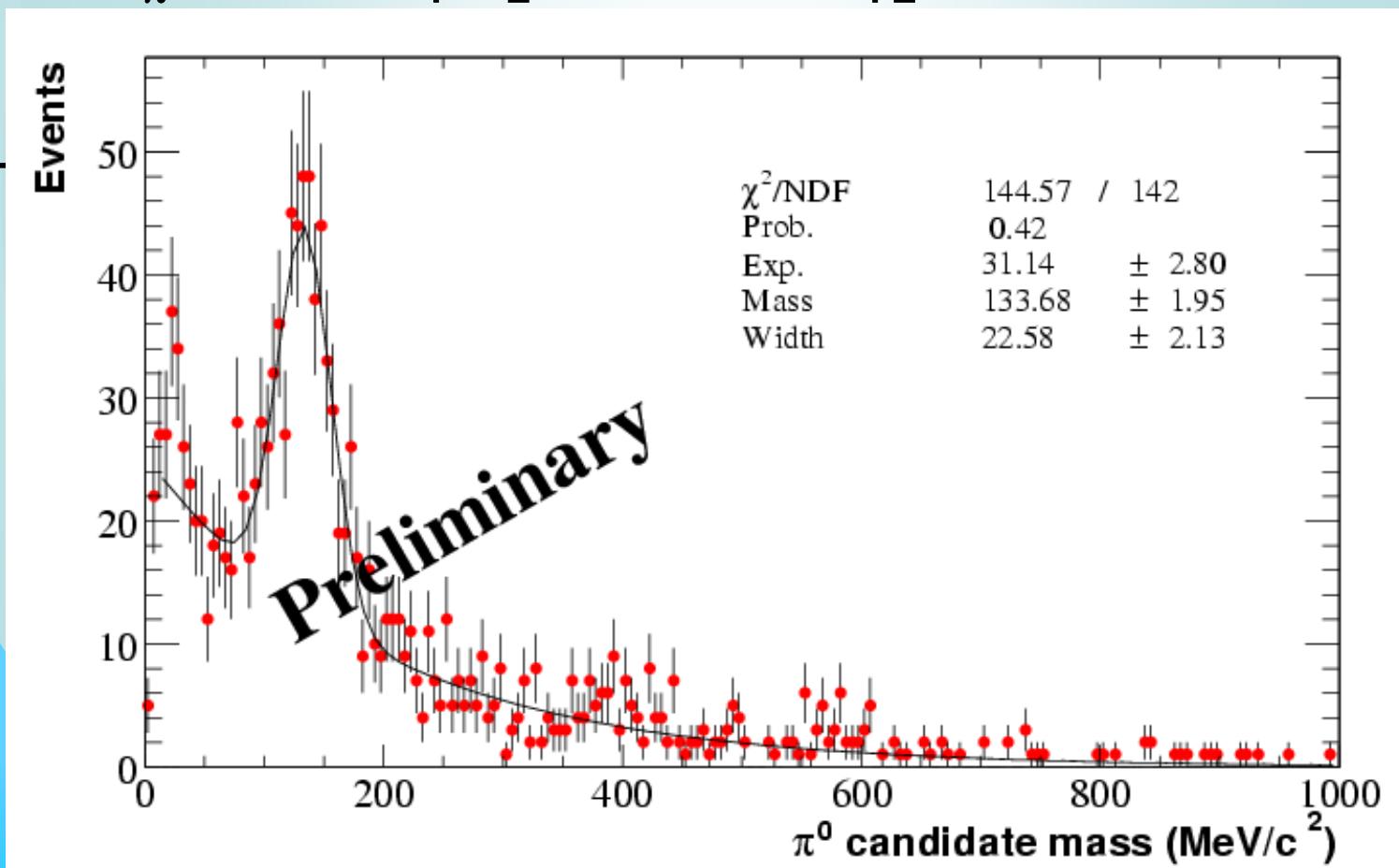
E = photon energy θ_{12} = opening angle

- tests energy calibration, angular reconstruction

Detector, calibration, etc. working well: two-ring mass plot

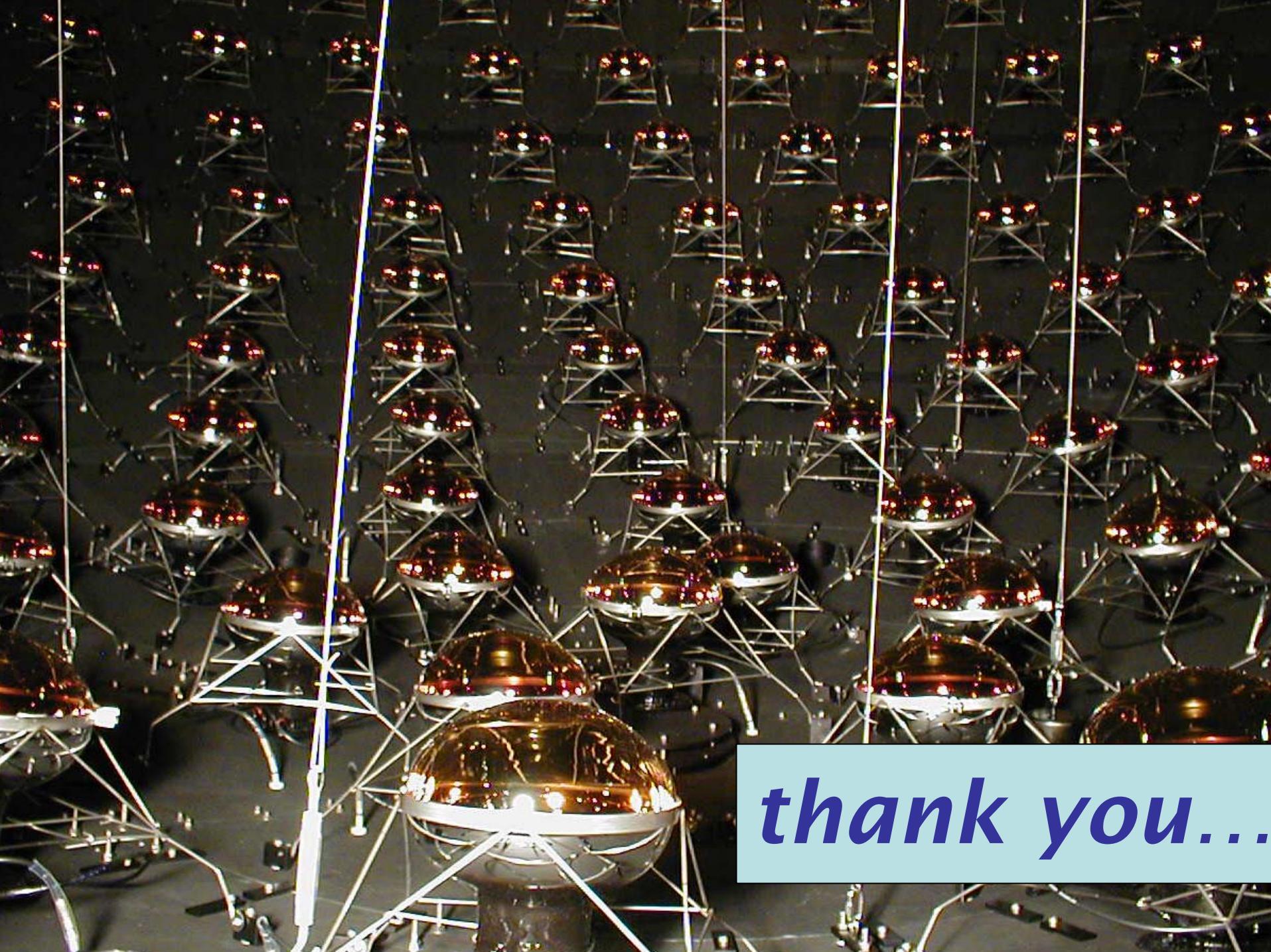
- Reconstructed $\gamma\gamma$ mass: π^0 peak

$$m_{\pi^0}^2 = 2 E_1 E_2 (1 - \cos \theta_{12})$$



CONCLUSIONS

- Neutrino oscillations are an established phenomenon
 - Oscillation parameters (Δm^2 , +c.) await definitive determination
 - MiniBooNE will decisively test the LSND signal – and is well underway
- Importance of result:
 - even if large Δm^2 (a la LSND) is NOT seen, MiniBooNE still makes an important contribution to understanding oscillation physics
 - if LSND signal is confirmed, this points to the existence of new particles (sterile neutrinos) or other new physics



thank you...

NEUTRINO OSCILLATIONS

signal & backgrounds

- signal: $\nu_\mu \rightarrow \nu_e$ oscillation via CC $\nu_e C \rightarrow e^- N$;
looking for electron events (“fuzzy rings”)
- backgrounds:
 - intrinsic ν_e beam contamination: $K^+ \rightarrow \pi^0 e^+ \nu_e$ (5%);
 $\pi^+ \rightarrow \nu_\mu \mu^+$, $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$
 - address: LMC, change decay length, HARP
 - misidentification I: NC π^0 production $\nu_\mu C \rightarrow \nu_\mu C \pi^0$. π^0 decays to $\gamma\gamma$; only one photon is seen
 - address: measure π^0 production cross-section (NC and CC), estimate decay asymmetry
 - misidentification II: CC ν_μ interaction $\nu_\mu C \rightarrow \mu^- N$, where captured muon fakes an electron
 - address: cosmic ray muons